NASA Conference Publication 2154

Synchronous Energy Technology

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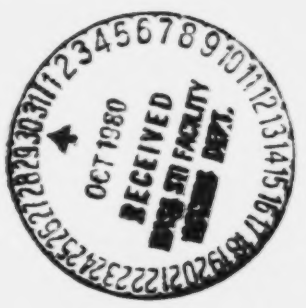
Proceedings of a symposium held at
NASA Lewis Research Center
Cleveland, Ohio
April 29-30, 1980



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PREFACE

The principal objective of the Space Energy Research and Technology program in OAST is to improve current capabilities for generating, storing, processing, and distributing electrical energy for use in space systems. With the advent of the Space Shuttle transportation system, NASA is actively involved in planning for synchronous orbit missions which utilize the launch capabilities of the Inertial Upper Stage (IUS). Technological advances in space-power generating capabilities are required for gaining the high performance that is required by the combination of user and launch vehicle characteristics. The two-day symposium at the NASA Lewis Research Center was held to allow experts from both NASA and the Airforce to review the synchronous energy technology requirements. The symposium provided a forum through workshops for discussion of the present program and for making recommendations about the specific technology efforts and the resources required to bring these efforts to fruition. To lay the foundation for the discussions, overviews of NASA and Air Force projected mission requirements as well as the present status of technology in the various disciplines were presented. Workshop groups were small, yet they contained more than sufficient expertise for lively and rewarding interchange of ideas. The free and informal exchange of ideas along with the dedication to produce a meaningful and coordinated set of recommendations made the meeting highly sucessful.

Sol H. Gorland
Conference chairman

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SYNCHRONOUS ENERGY TECHNOLOGY PROGRAM

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The power programs in NASA and DOD are presently structured towards providing the technology for future large space power systems. The synchronous energy technology program is a program to define the technologies required for future geosynchronous power stations and to collect and focus existing and new technology programs towards common structured goals. The output of the program will be a series of design data documents to provide design information and to transfer the technology to the involved community.

SYNCHRONOUS ENERGY TECHNOLOGY PROGRAM CONCEPT

- A TECHNOLOGY PROGRAM TO ENABLE GEO, LONG LIFE, POWER (≈25 kW, 10 yr)
- PROVIDE FOCUS FOR ADVANCED TECHNOLOGIES
- IDENTIFY NEW TECHNOLOGIES APPLICABLE TO GEO, HIGH POWER REQUIREMENTS
- INITIATE A CONTINUING EFFORT TO FACILITATE TECHNOLOGY TRANSFER

SYNCHRONOUS ENERGY TECHNOLOGY PROGRAM SYSTEM BENEFITS

- WITH CURRENT POWER SYSTEM TECHNOLOGY THE STS PERFORMANCE CAPABILITIES CAN POTENTIALLY PLACE A 10-kW POWER SYSTEM IN A GEO ORBIT.
- THE PROGRAM CAN PROVIDE A FOCUS FOR ADVANCED GEOSYNCHRONOUS SPACE POWER TECHNOLOGY EFFORTS.
- INTEGRATION OF THERMAL MANAGEMENT WITH POWER GENERATION PROVIDES SIGNIFICANT BENEFITS. AN INTEGRATED POWER SYSTEM COMBINING THE FUNCTIONS OF POWER GENERATION, DISTRIBUTION AND CONDITIONING WITH THERMAL MANAGEMENT WILL
  - INCREASE PERFORMANCE
  - ENHANCE RELIABILITY
  - REDUCE COMPLEXITY
  - LOWER WEIGHT
- AVAILABILITY OF HIGH POWER IN GEO IS MISSION ENABLING!
  - DOD SURVEILLANCE AND DEFENSE
  - COMMUNICATIONS PLATFORMS
  - ADVANCED TERRESTRIAL BENEFITS
- COMMERCIALIZATION OF GEO SPACE WILL REQUIRE CENTRAL POWER STATION GENERATION AND DISTRIBUTION TECHNOLOGY.

SET SYSTEM ASSUMPTIONS

- FREE FLYER
- GEO
- 10-YEAR LIFE
- DELIVER 25 kW AC/DC POWER TO USER (EOL)
- DISSIPATE 25 kW OF HEAT FROM THE USER
- DISSIPATE ~3 kW OF POWER CONVERSION LOSSES
- USER DOCKING FACILITY
- SHUTTLE - IUS LAUNCH (2269 kg)
- TECHNOLOGY READY IN 5 YEARS
- BATTERY STORAGE CAPACITY ≈2-1/2 kW hr PEAK POWER ≈50 kW
- DEPLOYMENT AT GEO

SYNCHRONOUS ENERGY TECHNOLOGY PROGRAM

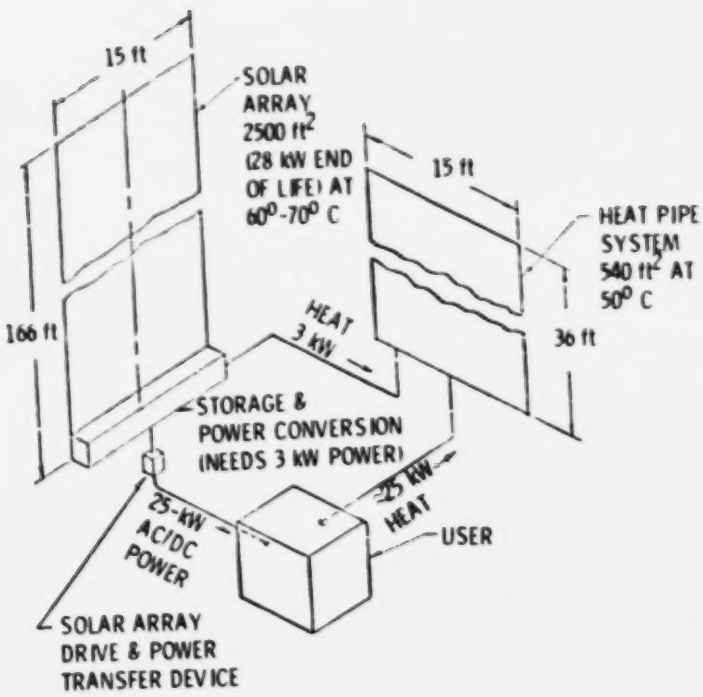
SYSTEM CONCEPTUAL DESIGNS

- ARRAY BLANKETS MAY INCORPORATE INTEGRAL THERMAL CONTROL FOR RADIATION OF POWER DISTRIBUTION AND USER THERMAL LOSSES.
  - SIMPLE STANDARDIZED THERMAL UMBILICAL

- CAPABILITY FOR PROVIDING REGULATED, CONTROLLED POWER FOR A VARIETY OF USER REQUIREMENTS.
  - STANDARDIZED VOLTAGE AND FREQUENCY WILL BE PROVIDED TO ALL USERS FOR PLUG-IN OPERATION. ADAPTABLE POINT OF LOAD (POL) CONVERTERS CAN THEN BE DEVELOPED TO MEET MULTIPLE USER REQUIREMENTS.

- INTEGRAL ARRAY/POWER CONVERSION/STORAGE SIMPLIFIES POWER MANAGEMENT INTERFACES.
  - POWER CONVERSION ON THE ARRAY SIMPLIFIES ROTARY POWER TRANSFER REQUIREMENTS.
  - INTEGRAL ARRAY/POWER CONVERSION REDUCES TRANSMISSION LINE LOSSES.

SCHEMATIC


15 ft
SOLAR ARRAY 2500 ft² (28 kW END OF LIFE) AT 60°-70° C
15 ft
HEAT PIPE SYSTEM 540 ft² AT 50° C
166 ft
HEAT 3 kW
36 ft
STORAGE & POWER CONVERSION (NEEDS 3 kW POWER)
25 kW HEAT
USER
25-kW AC/DC POWER
SOLAR ARRAY DRIVE & POWER TRANSFER DEVICE

SYNCHRONOUS ENERGY TECHNOLOGY PROGRAM

SYSTEM TECHNOLOGY GOALS

TO PROVIDE TECHNOLOGY FOCUS, A 25-kW, GEO FREE, FLYER POWER STATION WITH A GOAL OF AT LEAST 2.5-kW hr AND 28-kW HEAT REJECTION CAPABILITY, COMPATIBLE WITH SHUTTLE/IUS WILL BE BASELINE REQUIREMENTS.

TO ATTAIN TECHNOLOGY GOALS, ADVANCES REQUIRED ARE

(1) REPLACE NiCd BATTERIES WITH LONG-LIFE, HIGH-ENERGY-DENSITY STORAGE SYSTEM.

(2) REPLACE 28 V dc SYSTEM WITH HIGH VOLTAGE AC/DC DISTRIBUTION BUS.

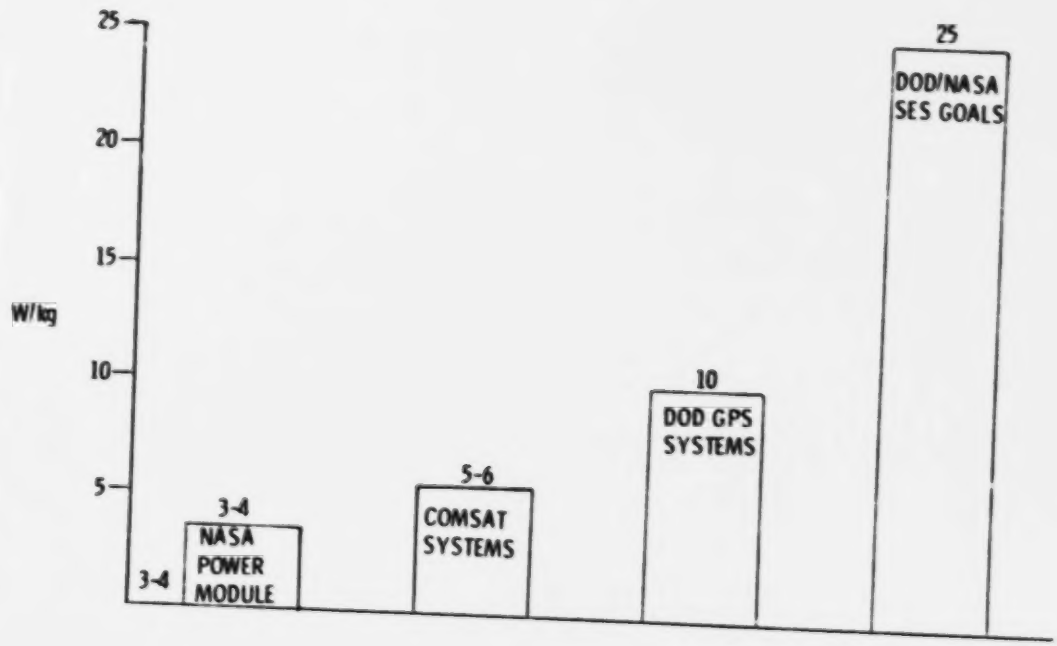
(3) ADDRESS INTEGRATING SEPARATE SOLAR ARRAY THERMAL CONTROL SYSTEM WITH INTEGRAL THERMAL CONTROL.

(4) INCREASE SYSTEM SPECIFIC POWER TO BE COMPATIBLE WITH STS CAPABILITIES FOR 25 kW IN GEO.

(5) RADIATION HARDENING.

(6) REPLACE CURRENT RETROFITTED POWER SYSTEM CONTROLS WITH INTEGRATED AUTONOMOUS FAULT PROTECTION SYSTEM.

TECHNOLOGY GOAL



SYNCHRONOUS ENERGY TECHNOLOGY PROGRAM

CANDIDATE SPECIFIC PROGRAM ELEMENTS:

(1) INTEGRAL SOLAR ARRAY/POWER CONVERSION AND THERMAL CONTROL SYSTEM

(2) HIGH VOLTAGE TRANSMISSION AND DISTRIBUTION (AC AND/OR DC)

(3) HIGH POWER ROTARY TRANSFER DEVICE

(4) POINT OF LOAD POWER CONVERSION

(5) SYSTEM/ENVIRONMENT INTERACTION CONTROL

(6) SOLAR ARRAY BLANKET/MATERIALS TECHNOLOGY

(7) APPLICATION OF ADVANCED STORAGE TECHNOLOGY

(8) STRUCTURAL/THERMAL/ELECTRICAL COMPOSITE MATERIAL TECH.

(9) LONG LIFE THERMAL CONTROL TECHNOLOGY

(10) HIGH TEMPERATURE ELECTRONICS

(11) SOLAR ARRAY CONCENTRATOR TECHNOLOGY

(12) RADIATION HARDENING

(13) AUTONOMOUS ENABLING SUBSYSTEMS

(14) THERMAL ENERGY TRANSFER

(15) SOLAR ARRAY THERMAL CHARACTERISTICS

SYNCHRONOUS ENERGY TECHNOLOGY PROGRAM

OBJECTIVE: TO DEVELOP AND EXECUTE A FOCUSSED TECHNOLOGY PROGRAM TO PRODUCE A DESIGN DATA BASE FOR FUNCTIONALLY INTEGRATED GEOSYNCHRONOUS ORBIT, SPACE POWER.

APPROACH: CONDUCT CONTRACT AND IN-HOUSE SYSTEMS AND TECHNOLOGY EFFORTS FOR A PROGRAM WHICH ALLOWS THE INTEGRATION OF THE MAJOR SUBSYSTEMS FOR SPACE POWER AND INCORPORATES THE TECHNOLOGIES REQUIRED WHICH ARE ENABLING OR CAN BE SHOWN TO BE COST EFFECTIVE OVER THE TOTAL MISSION LIFE CYCLE.

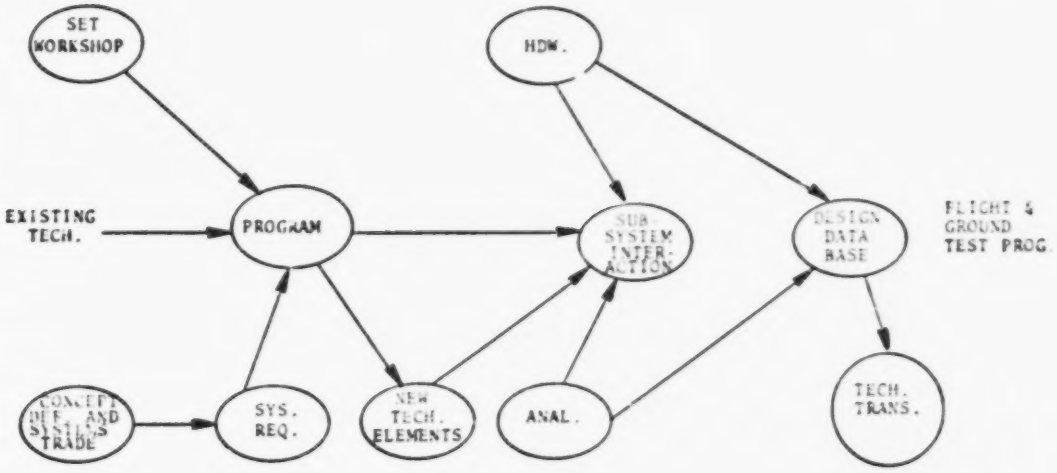
TECHNICAL MANAGEMENT APPROACH

REVIEW EXISTING TECHNOLOGY PROGRAMS AND THEIR POTENTIAL APPLICABILITY TO THE HIGH ORBIT SPACECRAFT ENERGY TECHNOLOGY PROGRAM.

SYSTEM TRADEOFFS PERFORMED ON SUBSYSTEM APPROACHES OF THE HIGH ORBIT SPACECRAFT ENERGY TECHNOLOGY SYSTEM PROGRAM WILL PROVIDE REQUIREMENTS FOR FOCUSSING THE EXISTING TECHNOLOGIES AND IDENTIFY THE NEW TECHNOLOGY ELEMENTS NEEDED.

SUBSYSTEM INTERACTION DATA BASED ON HARDWARE AND ANALYSIS WILL DETERMINE NEEDS FOR THE TECHNOLOGY VERIFICATION PROGRAM.

TECHNICAL MANAGEMENT APPROACH



SUMMARY OF ENERGY STORAGE TECHNOLOGY REQUIREMENTS

- ENERGY STORAGE CAN BE SINGLE HEAVIEST ELEMENT OF POWER SYSTEM
- REDUCE POWER TO 10% IN ECLIPSE BECAUSE OF WEIGHT OF BATTERIES REQUIRED FOR 100% POWER IN ECLIPSE.
- BATTERY TECHNOLOGY MUST ADVANCE FROM 18 (W hr)/kg TO 55 (W hr)/kg EVEN FOR REDUCED REQUIREMENT.

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NASA TECHNOLOGY PROGRAM OVERVIEW

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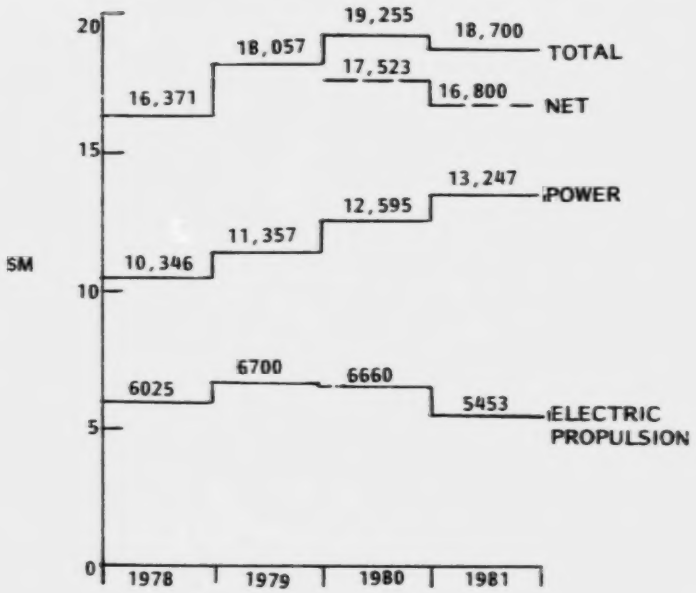
SPACE POWER AND ELECTRIC PROPULSION
TOTAL R & D ($K)



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PHOTOVOLTAIC ENERGY CONVERSION (3.2M/58 DPY)

THRUST	APPROACH
o CELL R&T	
→ 2 kW/kg	- 18% Si Cell - 50 μm Si Cell - CVD GaAs/Concentrator Cell - Multibandgap
→ LIFE (15%, 30 YR GEO)	- Radiation Immunity/GaAs - Annealing/Rad. Handbook
→ $5/W	- CBC/Large Area Si/PEP Cell - Non-Vacuum Processes/DOE Line
o LOW COST BLANKETS/ARRAYS → $30/W AT 100 kW	- Concept Trades - Module Development - Low Cost SEP Blanket
o HIGH PERFORMANCE BLANKETS/ARRAYS → >300 W/kg GEO/PLANETARY	- Concentrator Concepts - Planar Thin Cell Blanket

POWER MANAGEMENT AND DISTRIBUTION (3.4M/62 DPY)

THRUST	APPROACH
o COMPONENTS, CIRCUITS, SUBSYSTEMS → >100 kW → HIGH VOLTAGE → LIFE	- Power Transistors, Diodes, Switches, Capacitors - Converters, CDVM, Inverters - APSM (Planetary) - AMPS (LEO) - AC/DC Model
o ENVIRONMENTAL INTERACTIONS	- Charging Design G/L/NASCAP - HV Plasma Interactions/Design GL
o THERMAL MGMT	- Concept Trades - Acquisition/Transport/Rejection Components

CHEMICAL ENERGY CONVERSION AND STORAGE (2.7M/43 DPY)

THRUST	APPROACH
o HIGH ENERGY DENSITY	Li Primary
→ 1MJ/kg	Li Secondary
	NaS Secondary
o HIGH CAPACITY	Toroidal NiCd
→ 100 kW LEO	Fuel Cell/Electrolyzer
25 kW GEO	Ni H
o FUNDAMENTALS	NiCd Reconditioning
→ Life	NiCd Failure Model
Understanding	Separators

THERMAL TO ELECTRIC CONVERSION (1.7M/12 DPY)

THRUST	APPROACH
o POWER FOR NEP	- Joint Planning with DOE/AF
→ 20 kg/kW	- Requirements Analysis/Syst Design
	- Converter Trades
	TE/TI Experimental
	Brayton Analytical
	- Heat Pipe/Radiation Coupling
	- GDS Planning
o RTG CONVERSION	- Advanced Materials/Converters
→>10 W/kg	
o STG DEVICES	- Panel Designs/Tests

ADVANCED ENERGETICS (1.3 M/24 DPY)

THRUST	APPROACH
o ADVANCED CONCEPT ASSMT	- OVERALL SOLICITATION/ASSESSMENT/REVIEW/WORKSHOPS - SELECTED 'SEED MONEY' SUPPORT E.G., INERTIAL ENERGY STORAGE PLASMA HEAT PIPE SODIUM TE CONVERTER LASER ANNEALING/WELDING SPECTRA/THERMO PHOTOVOLTAICS* LIQUID DROP/PARTICLE RADIATORS FLYWHEEL STORAGE
o LASER POWER GENERATION & TRANSMISSION	- SOLAR PUMPING - NUCLEAR PUMPING - RECEIVERS

* CURRENTLY SUPPORTED IN PHOTOVOLTAIC OBJECTIVE

SYNCHRONOUS ENERGY TECHNOLOGY (SET)

NEED: MANY USAF & NASA MISSIONS WILL REQUIRE HIGH POWER IN HIGH ORBITS

- USAF: SPACE BASED RADAR, SPACE SURVEILLANCE, SPACE WEAPONS
- NASA: COMSATS, DIRECT BROADCAST, ELECTRONIC MAIL

OBJECTIVE: TO ASSURE TECHNOLOGY READINESS OF SYNCHRONOUS ORBIT POWER SYSTEMS OF > 25KW BY 1985

BENEFITS: ENABLING WITHOUT A NEW STS
AUTOMATED TO REDUCE COSTS AND VULNERABILITY AND TO INCREASE RELIABILITY
MULTIPURPOSE MODULE CONCEPT

APPROACH: DEVELOP DRAFT PROGRAM PLAN AT NASA/USAF WORKSHOP/MTG - APRIL/MAY 1990

PLANNING

- NASA ADVISORY COUNCIL - SSTAC REPORT 1979

HIGH BENEFIT	MODERATE BENEFIT	LOW BENEFIT
- >100 W/KG SILICON ARRAY	- AUTOMATED POWER SYST	- ADVANCED NiCd
- > 33 WH/KG Ni-H	- 300-1KV BUS/COMPONENTS	
- 100-300V BUS/COMPONENTS		
- >200 W/KG CONCENTRATORS		
- > 50 WH/KG INERTIA WHEELS		
- >50 WH/KG METHAL SULPHER BATTERY		
- >50 WH/KG H_2O_2 SYSTEMS		

- NASA/AF SET TECHNOLOGY PLANNING
  - FOCUS TECHNOLOGY TOWARD GEO, >25 kW, 10YR
  - IDENTIFY NEW APPROACHES/CONCEPTS
  - ESTABLISH GOALS/ROLES/RESOURCES

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AIR FORCE SPACE POWER TECHNOLOGY PROGRAM

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AF Wright Aeronautical Laboratories
Wright Patterson AFB, Ohio

For the past several years the USAF program in spacecraft power technology has concentrated on obtaining major improvements in solar cell efficiency, solar array survivability, and secondary battery energy density. Because of the nature of USAF requirements in space and the limited resources available for the technology program, these areas offered the highest potential and the widest applicability. Further selectivity within these categories resulted in major programs in gallium-arsenide solar cells, nickel-hydrogen batteries, and radiation-resistant, high-temperature solar array components. These programs have been quite successful with the attainment of 18 percent GaAs solar cells, 15 W h/lb Ni-H_2 batteries, and array systems capable of operating at 500° C in high nuclear radiation environments. Future programs in these areas promise even greater improvements in these basic solar power system technologies.

Results of recent DOD space power studies show a trend towards higher power levels for future DOD missions. Consequently, the major new thrusts of the DOD space power technology program center on the development of military power systems which will extend capabilities to the 100 kW_e range by the year 2000 for the new classes of missions, while maintaining technology applicability to the 1 to 10 kW_e present (and continuing) mission class. Although NASA and COMSAT programs will provide space users with high power capabilities, they do not satisfy all military requirements, and the development of a high level, high-power-density survivable space energy technology is necessary. Plans call for technology, subsystem, and "integrated" power system efforts which emphasize performance, reliability, autonomy, and survivability. Distinct roles for both nuclear and solar power technology are envisioned.

In the next 5 years several new technology areas will be added to the baseline programs. Because of increasing military satellite power requirements and more complex spacecraft operations, efforts will be initiated to improve spacecraft power processing and thermal management. As these efforts mature, a program to integrate all technologies to provide high-power total-system capabilities will be initiated.

This briefing summarizes the military spacecraft power subsystem design requirements, development goals, and planned technology efforts.

The mission drivers of performance (weight and volume), hardening (survivability), autonomy, reliability, and miniaturization influence space

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mission effectiveness, cost, and in some cases feasibility in both direct and indirect fashions (fig. 1). Power system technology is mission enhancing in some cases and mission enabling in others. Both classes must be addressed in development efforts.

Survivability requirements are driven primarily by nuclear weapon and laser weapon threats (fig. 2). Both hardening and other survivability techniques (e.g., threat avoidance) are under consideration. Details of particular threats and survivability and/or hardening techniques are classified. Concentrating photovoltaic systems may find use for high threat environments, by virtue of the shielding of the cell affected by the optical components.

Increasing autonomy, that is, independence from ground station command and control, is required of military space systems (fig. 3). Power autonomy can be attained by self-management of power and fault processing, improved performance, and enhanced reliability.

Reliability (fig. 4) is in itself an important design driver for military space power systems. Military missions for LEO require 3- to 5-year life, while the GEO mission requires a 7- to 10-year life.

Performance requirements for military applications generally fall within the 1 to 5 kW_e regime for early applications (1980 to 1985) and may grow to the 25 to 50 kW_e range for some advanced surveillance applications in the 1985 to 1995 period (fig. 5). Isotope dynamic systems may find use for some special purpose applications (e.g., high hardness). Future high power applications may dictate development of a reactor power system for higher power.

Figure 6 shows the anticipated performance improvement trends for solar power systems obtainable via technology transition from present photovoltaic and battery types to more advanced devices. Major reductions in solar array weight will be realized through cell efficiency improvements via silicon to gallium arsenide to multibandgap cell transitions. Energy storage weight reductions will be placed by transition from nickel-cadmium to nickel-hydrogen to high-energy-density molten salt battery technology.

Figure 7 illustrates anticipated performance versus power level trends for reactor-static conversion systems. The technology for heat-pipe-cooled reactor thermoelectric systems could be system ready by early 1990's if development and qualification resources are invested in the 1980's. Higher temperature, higher performance reactor thermionic systems based on the same heat-pipe-cooled core to converter concept could yield energy densities of 50 W/lb or more, as compared with 25 W/lb for solar power, depending on the specific design concept and energy conversion scheme. Presently, DOE and NASA are pursuing only limited component technology development programs; major resource investments are required beyond the modest levels presently being invested if reactor power systems are to be prototyped and flight qualified and to become operational. The thrust of the high power missions for the 1980-2000 period may give impetus to enhance development. The nuclear reactor power system's projected energy density, inherent compact-

ness, and probable ruggedness make it an ideal candidate for high power military applications requiring maneuverability, survivability, and long life.

The present Air Force power system R&D thrust is shown in figure 8. It encompasses basic (6.1), exploratory (6.2), and advanced development (6.3) in solar photovoltaics, metal gas batteries (e.g., Ni-H_2), and systems level power processing and thermal control. Coordination with DOE on reactor state of technology and applicability to military missions is also pursued.

Figure 9 shows a composite space power technology 6.1, 6.2, and 6.3 resource expenditure plan for the FY 1980-86 period. The Vanguard mission areas listed are those approved or advanced systems concepts which are anticipated users of this technology.

Figure 10 lists ongoing and planned development work unit tasks in the solar cell/array area. Major future thrusts are in GaAs and the multi-bandgap area.

The impact of this advanced array area is shown in figure 11, which compares conventional 8-mil silicon 5-mil coverglass flexible array weight and deployed area with improvements anticipated with advanced cell types.

Individual array hardening tasks against nuclear, laser, and particle beam type threats are shown in figure 12. Laser hardening of solar arrays is currently being pursued by the AFWAL Aero Propulsion Laboratory and the Materials Laboratory under both 6.2 and 6.3 (SMATH) programs.

Figure 13 shows the work unit breakout and time oriented development goals for battery technology. The major emphasis within the Air Force is in Ni-H_2 technology, now under advanced development. More advanced high-energy-density-battery (HEDB) concepts are presently being explored under 6.2 efforts and will enter advanced development in FY 1983.

The combined effects of improved array and battery performance is illustrated in figure 14. The shaded area represents the schematic weight decrease attainable in transitioning from Ni-Cd to Ni-H_2 and to higher performance, molten electrolyte batteries.

The tasks associated with thermal control and high power management, and their objectives are shown in figure 15. Thermal energy storage concepts could be used for heat driven cryocoolers. Thermal management and power processing for high power systems represent formidable outyear goals.

The evolving military space mission requirements are described in figure 16. Military operational uses of space were quite limited in the early 1960's. During the 1980's space will become an increasingly important military theater and by the turn of the century an important and vital segment of military communications, command, control, and force assessment. The future military use of near-Earth space will be to support and defend evolving civilian and military operations in space and to conduct traditional

military functions supporting national defense objectives. Current and envisioned mission areas and functions in the mission categories of communication, surveillance, space operations, and defense impact power technology requirements.

Figure 17 illustrates a conceptual design for a space based radar (SBR) system. Several design alternatives are presently being studied by the Air Force, including a nuclear reactor powered configuration. National security requires surveillance inspection and monitoring of an adversary's weapon forces and their movements; this surveillance mission focuses on detection and attack warning. Power levels of approximately 10 to 100 kW are envisioned for radar and LWIR systems, due primarily to the need for active cryogenic cooling of the sensor.

The envisioned power requirements range as a function of IOC are shown in figure 18. The mission requirements and planned spacecraft developments give rise to both evolutionary and revolutionary power system design requirements. These requirements include life, performance, reliability, survivability, availability, and cost. The requirements may be divided into two major need categories, low power (evolutionary needs) and high power (revolutionary needs). All six of the power system design requirements are strongly influenced by the operational orbits of interest. Military orbits of interest include low Earth (400 to 600 m), both inclined and polar, half synchronous, synchronous, elliptical, and supersynchronous orbits. Interest in the later two orbit categories is based on their survivability advantages. The variety of orbits give rise to a variety of natural radiation dosages, a wide range of solar and eclipse conditions, diverse ambient thermal radiation environments, and a variety of potential weapons threat environments which must be addressed by the system designers.

The areas of common technical needs for the Air Force and NASA are summarized in figure 19. The growth towards 25 to 50 kW after 1985 seems certain. The NASA high power missions will likely center on large communication satellite applications; the military applications by surveillance missions. Both agencies must address STS-spacecraft design compatibility; throw weight to all but a few LEO's remains a design problem, hence a driver for high performance power systems. Improved array efficiency and energy storage density pace these performance needs. Reliability, life, power conditioning, and component weight introduce new performance requirements for high power systems which remain to be explored.

SPACE SYSTEM PARAMETERS

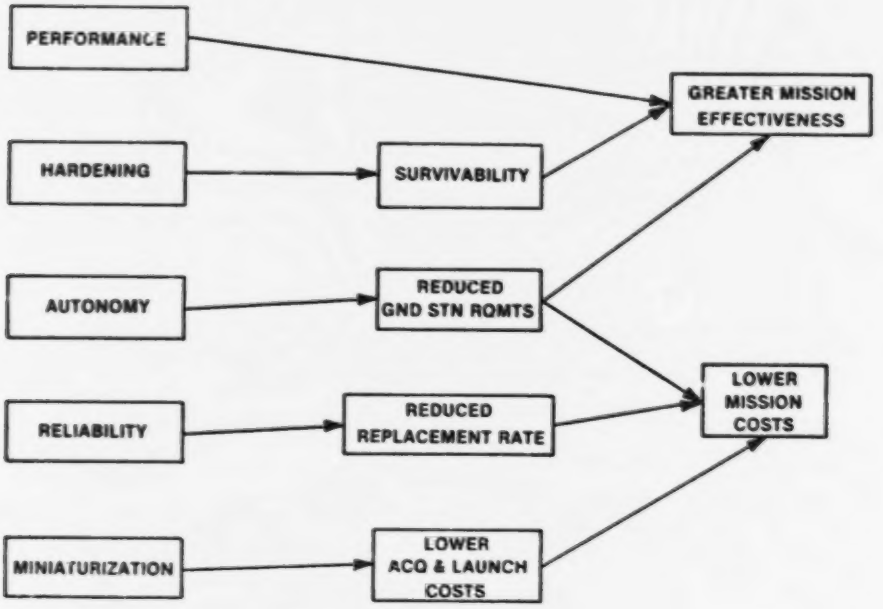


FIGURE 1

SURVIVABILITY

IMMEDIATE REQUIREMENTS (1980-1985)

- NUCLEAR HARDENED ARRAYS (10 x JCS)
- LOW LEVEL LASER HARDENED ARRAYS (SMATH I)
- FLEXIBLE ROLL-UP ARRAYS
- HARDENED, RECONDITIONABLE BATTERIES

MID-TERM REQUIREMENTS (1985-1995)

- CONVENTIONAL WEAPON HARDENING
- HIGH LEVEL LASER HARDENING (SMATH IV)
- INCREASED NUCLEAR HARDENING
- CONCENTRATOR ARRAY SYSTEMS
- THERMAL MANAGEMENT SURVIVABILITY

FIGURE 2

AUTONOMY

IMMEDIATE REQUIREMENTS (1980-1985)

- LOW SIGNATURE SYSTEMS
- HIGH EFFICIENCY SOLAR ARRAYS
- HIGH PERFORMANCE POWER SYSTEMS

MID-TERM REQUIREMENTS (1985-1995)

- FAULT-TOLERANT BATTERY
- ULTRA-PERFORMANCE HIGH POWER SYSTEMS
- SMALL AREA SOLAR ARRAYS
- THERMAL ENERGY SYSTEMS

FIGURE 3

RELIABILITY

IMMEDIATE REQUIREMENTS (1980-1985)

- HIGH EFFICIENCY, LOW DEGRADATION SOLAR ARRAYS
- LONG LIFE NICKEL-HYDROGEN BATTERIES
- IMPROVED LOW ORBIT BATTERY CYCLE LIFE

MID-TERM REQUIREMENTS (1985-1995)

- 10-15 YEAR POWER SYSTEM LIFETIMES
- REDUCED BATTERY COMPLEXITY
- LOW ORBIT AND SYNC ORBIT POWER MODULES

FIGURE 4

PERFORMANCE

IMMED'ATE REQUIREMENT (1980-1985)

□□□INCREASED PRIME POWER (1-5KWe)

- COMMUNICATION NAVIGATION METEOROLOGICAL SYSTEMS
- GEOSYNC ORBIT WEIGHT CONSTRAINTS
- SHUTTLE VOLUME / GEOMETRY CONSTRAINTS
- HARDENED SOLAR ARRAYS/Ni-H2 BATTERIES
- ISOTOPE DYNAMIC SYSTEMS

MID-TERM REQUIREMENT (1985-1995)

□□□LARGE POWER DEMANDS (25-50KWe)

- DEFENSE AND SURVEILLANCE SYSTEMS
- SEVERE LIMITING GEOSYNC ORBIT WEIGHT CONSTRAINTS
- MODULAR SOLAR ARRAY/ADV BATTERY SYSTEMS
- NO REACTOR PROGRAM UNDERWAY

FIGURE 5

SOLAR POWER SYSTEMS

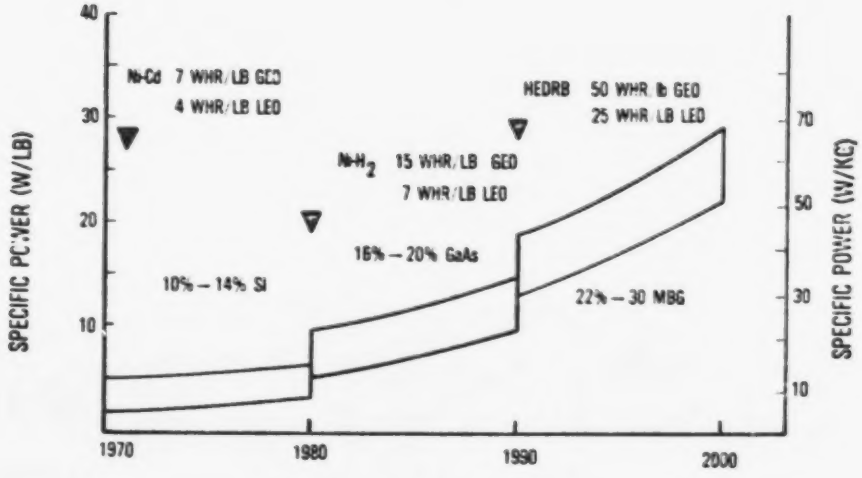


FIGURE 6

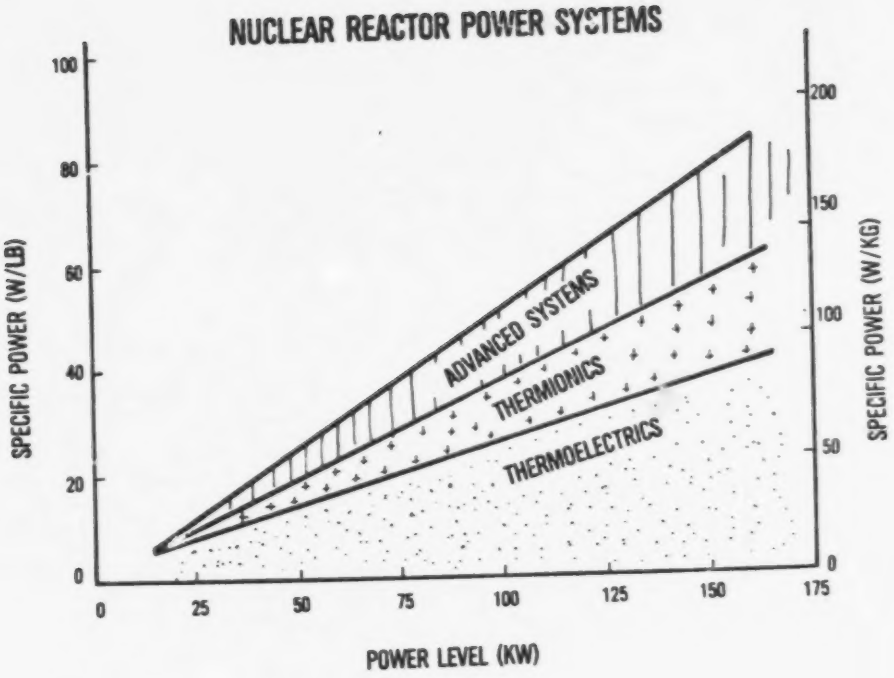


FIGURE 7

ENERGY CONVERSION BRANCH

SPACE POWER THRUST

- PROVIDE THE BASIC, EXPLORATORY, AND ADVANCED TECHNOLOGY FOR SPACE ELECTRICAL POWER SYSTEMS
- SOLAR CELLS, SOLAR ARRAYS, METAL-GAS BATTERIES
- LIGHTWEIGHT, LOW VOLUME, NUCLEAR AND LASER HARDENED
- PROVIDE HIGH PERFORMANCE LOW POWER SYSTEMS
- DEVELOP HIGH POWER, SYNCHRONOUS ORBIT CAPABILITY
- PROVIDE TECHNOLOGY FOR SPACE THERMAL ENERGY SYSTEMS
- KEEP ABREAST OF SPACE NUCLEAR REQUIREMENTS AND TECHNOLOGY

FIGURE 8

SPACE POWER THRUST

TPO NO. 4

DEVELOPMENT GOALS: SD-1, SD-1, SD-3, SD-5, SD-6, C³-1-6, TW-1, RI-1, L&OS

LABORATORY GOALS: HARDENED SPACECRAFT POWER SYSTEMS

VANGUARD MISSION AREAS SUPPORTED: STRATEGIC DEFENSE (SDSP, ASAP, SBR, DEW, DSSS); TACTICAL WARFARE (SDSP); RECCE/INTEL (ASAP, SBR); COMMAND CONTROL, COMMUNICATIONS (SDSP, SSS, DSCS, GPS, SATCOM); LAUNCH & ORBITAL SUPPORT; ENERGY

	FUNDING $1000's						
THRUST SUBELEMENTS	FY80	FY81	FY82	FY83	FY84	FY85	FY86
6.1	300	350	350	400	400	500	500
6.2	1344	1230	2327	2561	2865	2860	3605
6.3	1650	2300	1945	3200	5300	5500	7700
OTHER	300	500	(2000)	(2000)	(3000)	(5000)	(5000)
TOTAL	3594	4380	4622	6161	8565	8860	11805

FIGURE 9

SOLAR CELL DEVELOPMENT

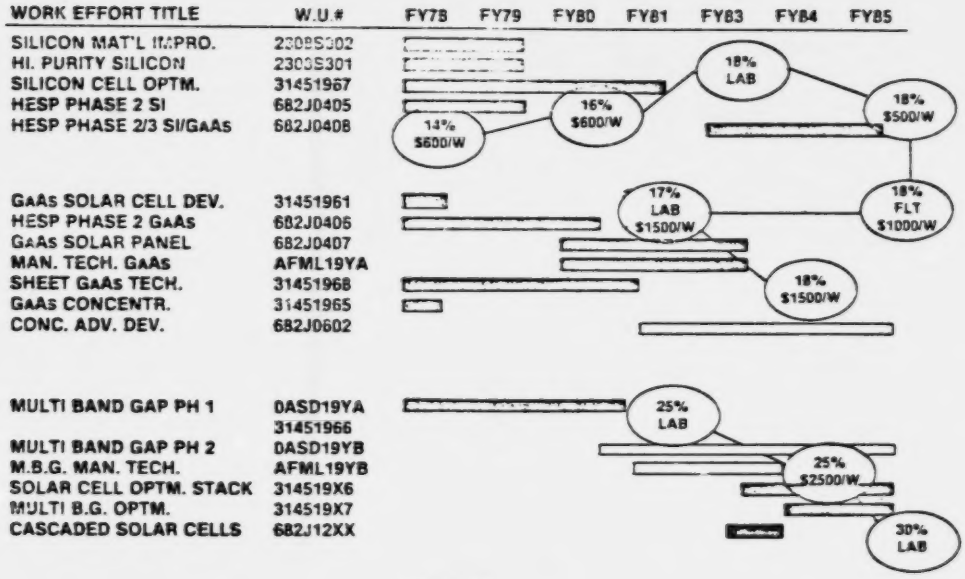
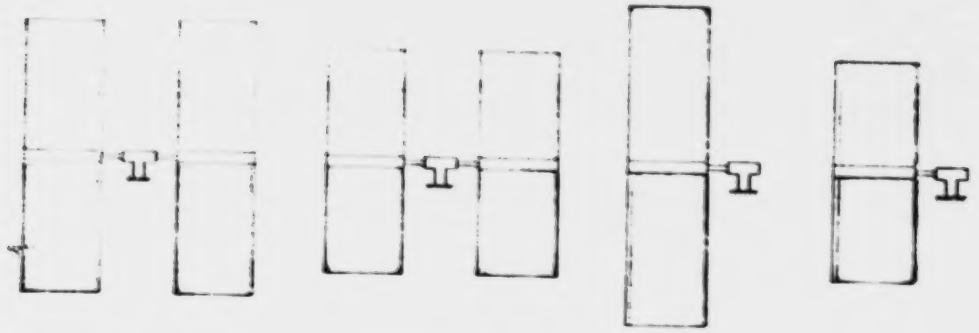


FIGURE 10

IMPACT OF ADVANCED SOLAR CELL TECHNOLOGY

(2KWe - 7 YRS. SYNC. ORBIT EOL)



CONVENTIONAL SILICON	ADVANCED SILICON	GALLIUM ARSENIDE	MULTI BANDGAP
AREA 350 FT2	288 FT2	205 FT2	141 FT2
WEIGHT 215 LBS	187 LBS	170 LBS	145 LBS

FIGURE 11

SPACE POWER THRUST ROADMAP

WEAPON HARDENING

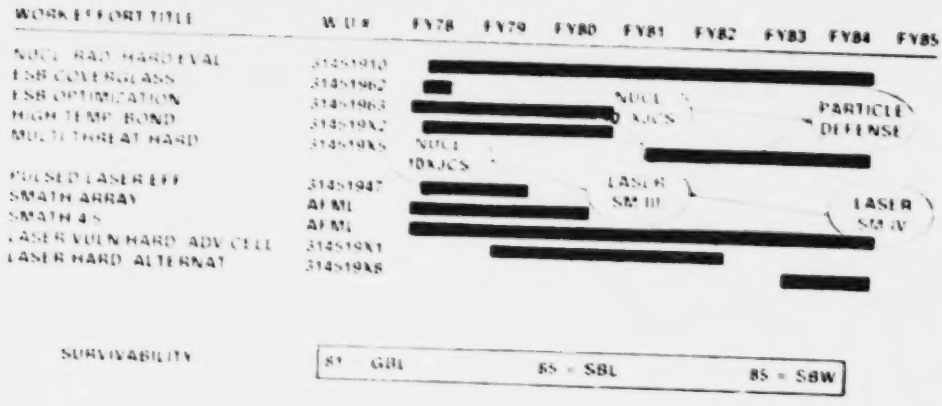


FIGURE 12

SPACE POWER THRUST ROADMAP

ELECTRICAL ENERGY STORAGE

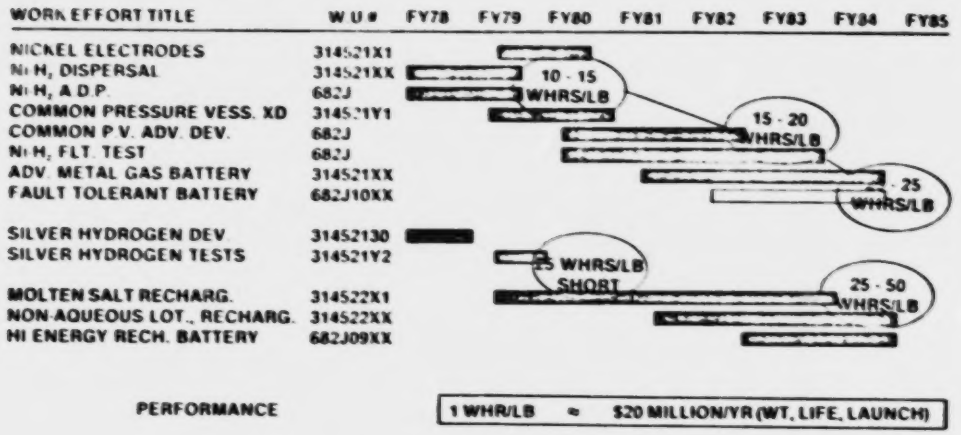
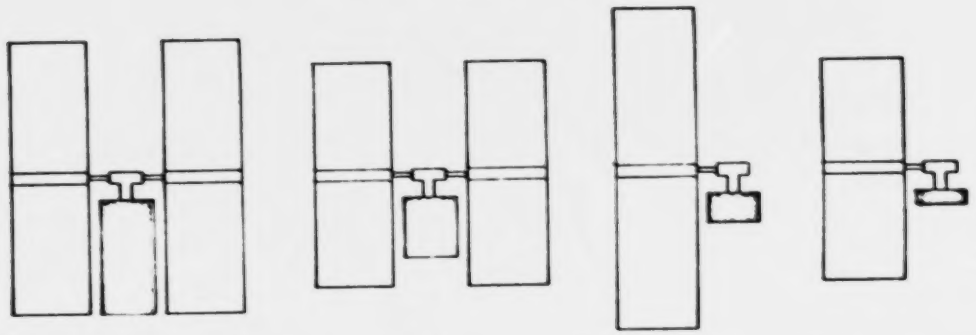


FIGURE 13

ADVANCED SPACE POWER SUPPLY TECHNOLOGY

(2 KWe - 7 YRS SYNC. ORBIT EOL)



CONVENTIONAL SILICON	ADVANCED SILICON	GALLIUM ARSENIDE	MULTI-BANDGAP
11% EFFICIENT SOLAR CELLS	145%	16%	25%
CONVENTIONAL Ni Cd BATTERY	**ADVANCED Ni Cd**	**Ni-H2**	**HEDRB**
4 WATT HRS/LB BATTERY	7 W-HRS/LB	18 W-HRS/LB	40 W-HRS/LB

FIGURE 14

SPACE POWER THRUST ROADMAP
THERMAL AND HIGH POWER

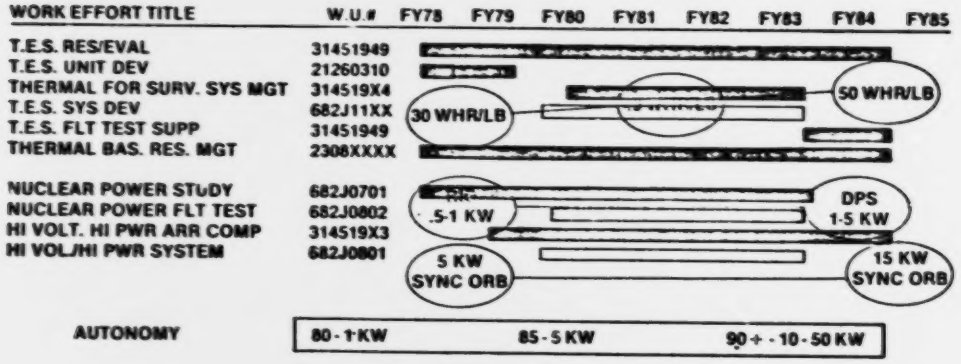


FIGURE 15

SPACE POWER THRUST
THE FUTURE

	1960	1980	2000
SCENARIOS			
STRATEGIC			
USSR	UNSALTED	SLIGHTLY SALTED	HEAVILY SALTED
OTHERS	NUCLEAR CONTROL	NUCLEAR PROLIFERATION	TOTAL PROLIFERATION
TACTICAL			
FIRST CLASS CAPABILITY	FEW	MANY	MAJORITY
SPACE DEPENDENCE/UTILIZATION			
STRATEGIC SURVEILLANCE	NONE	IMPORTANT	CRITICAL
TACTICAL SURVEILLANCE	NONE	SOME	IMPORTANT
TACTICAL NECESSITY	NONE	HELPFUL	NECESSARY
COMMUNICATIONS	NONE	50 %	100 %
SPACE OFFENSE	NONE	NONE	SOME

FIGURE 16

SBR Conceptual Design

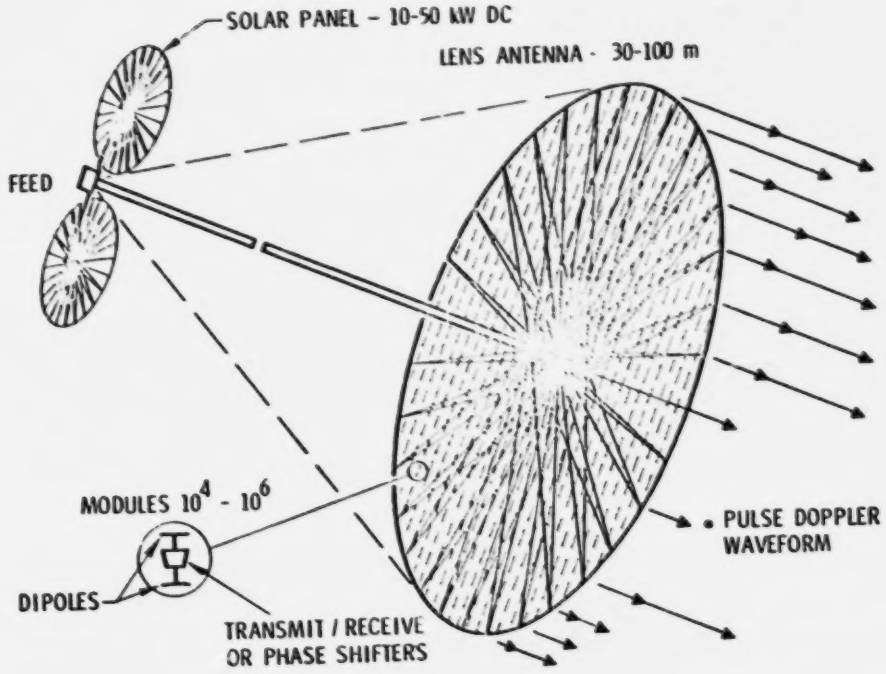


FIGURE 17

SPACECRAFT POWER REQUIREMENTS 1980 - 2000

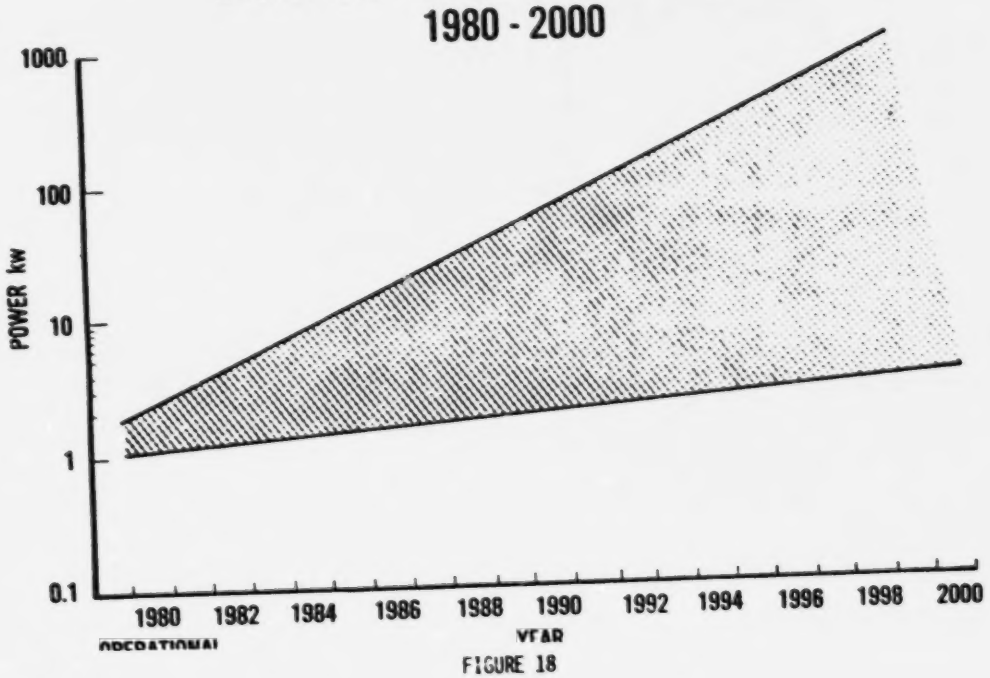


FIGURE 18

AREAS OF COMMONALITY

25 - 50KW POWER REQUIREMENTS (1985+)

SHUTTLE/IUS LAUNCH COMPATIBILITY

HIGH PERFORMANCE/LOW COST GOALS

ELECTRIC POWER/THERMAL MANAGEMENT REQUIREMENTS

FIGURE 19

N80-33469

SPACECRAFT SYSTEM OVERVIEW OF SPACE POWER AT GEOSTATIONARY EARTH ORBIT

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National Aeronautics and Space Administration
Washington, D.C.

Increased power at Geostationary Earth Orbit (GEO) at an affordable cost will have a large impact on spacecraft at that orbit. This paper discusses the OAST Spacecraft Systems Office's goals, power requirements at GEO, GEO environment and design considerations, power system elements and opportunities for technological improvements, and a communication example showing the value of additional power.

Introduction

The Spacecraft Systems Office's goal, Figure 1, is to define and implement new technology tasks that will provide cost effective operational spacecraft for the 1990's that meet new challenging mission performance requirements at an affordable reduced cost. In Figure 2 the office addresses three classes of spacecraft: large space systems at Low Earth Orbit (LEO); advanced spacecraft at Geostationary Earth Orbit (GEO); and advanced planetary spacecraft. This paper discusses those program goals and performance requirements devoted specifically to this meeting's subject, space power systems at GEO.

Power System Requirement at GEO

The Office of Aeronautics and Space Technology (OAST) maintains a NASA mission model which documents NASA's 5-year planning plus hopeful missions for the future. Figure 3 shows a summary of the GEO mission model presented at a meeting of this group in December 1978. Figure 4 shows similar information taken from the model in April 1980. A comparison of these two figures shows that the model is becoming more conservative. Storm sat, disaster warning, and global navigation have been dropped from the model. The requirements of the satellite power system have been reduced significantly. The global communication system has been replaced by the 20/30 program. A conclusion that can be made from comparing these two figures is that there is a continuing requirement for power up to 10 kw and the additional power up to 75 kw will be useful in the future. Consistent with OAST's goals, power technology advancements should be accomplished at an affordable cost.

GEO Environment and Design Considerations

GEO is a hostile environment that has an impact on a power system design. Spacecraft charging at GEO must be evaluated and understood. Figure 5, trade-off studies must be conducted to evaluate the impact of different levels of spacecraft grounding and shielding. The high radiation GEO environment rapidly degrades materials, parts and components. This is particularly important because we are facing requirements for increasingly longer life. Current life requirements are for two to three years with goals of from five to seven years and future requirements identified for up to twenty years. The degradation and life requirements are further aggravated by the fact that system performance requirements are defined in terms of "end of life" performance. Current brute force solutions to long life all result in increased weight. The technology challenge is to achieve 20 year performance life time with reduced weight and at reduced cost.

The present transportation system to GEO involving the Shuttle IUS combination makes an on-orbit maintenance philosophy prohibitively expensive if not impossible. Systems designed for GEO must meet spec performance with little or no scheduled maintenance. This means reliability is a continuing requirement. The present techniques are all using "pedigreed" parts which involve extensive testing to meet tight reliability requirements and are expensive. It is clear that the technologist must find new solutions to providing this reliability at significantly reduced costs.

The technologist must also maintain a constant awareness of the manner in which his designs drive implementation costs. The affordability issue of future space missions has put a major new emphasis on awareness of controlling cost drivers with new technology. Continuing work with current materials and the development and application of new materials with an awareness of cost, will result in the development of cost-effective designs. The significant challenge is to develop and verify these new materials and designs for the GEO environment.

The application of automation techniques is expected to reduce costs and improve performance of new designs in several ways including, but not limited to: self test, management of redundant paths, fault tolerant design permitting significant degradation within spec, and the elimination of costly, continuing ground operations.

The onboard spacecraft power defines the data management system capacity in bits/sec. It also defines the size and cost of ground receivers. The spacecraft power system provides interface to all spacecraft services. More power on orbit at decreased cost will result in a major redistribution of priority spacecraft

services. More power on orbit also will impact the design and use of ground receivers.

Power system weight is a technology challenge at GEO. The power system for communication satellites historically has ranged from 16-20% of total spacecraft weight.

Figure 6 lists some of the spacecraft system characteristics that will be influenced by a forecast expansion of available power. Current spacecraft are designed by the integrated analysis and systematic distribution of spacecraft resources. Power is one of the budgeted resources. If you can increase the available power at no increase in weight and a decrease in cost, the total spacecraft performance can be improved. Added calibration and temperature control can improve the performance and life of the attitude control system. Increased power can simplify the complex electronic circuitry that is necessary for signal computation and conditioning. Additional power will improve design margins of electronics, and will redistribute spacecraft weight and performance. Spacecraft system design studies are necessary to determine the optimum utilization of more onboard power.

An Illustrative Example

A 1000 beam, high power, short terrestrial tail, proliferated receiver communication system has been chosen as an example (see Figure 7) to illustrate the tremendous impact larger quantities of affordable space power can base on future programs. This system would locate a spacecraft at a longitude East of the United States to optimize the incident of sunlight on the arrays during periods of peak traffic at night between the United States and Europe. It would base a multiplicity of small receivers located across the country.

The shorter ground links required with many receiver stations will tend to reduce the total system costs. Link characteristics are shown on Figure 7 and a bit flow rate about equal to the current national telecommunications experience was assumed with a market of 80×10^6 users. These assumptions calculate to an on orbit requirement of approximately 75 kw of power.

Under certain reasonable cost assumptions it has been determined a communication system that has many small diameter receivers with short ground links is a highly competative low cost system. Examination of a variety of advanced communication schemes involving proliferated interacting users shows that if we can achieve a goal of 100 kw systems at $\$100(10)^6$ for 10 year operational life, the expanded power system can provide sufficient system cost reduction compared to present projected system cost to support the economics of such a new communication system.

Thus affordable space power can open the door to an exciting

new communication system that will stimulate the need of a large new expanded terrestrial system. The ground portion of this system will materialize as an expanding new industry.

Major Power Subsystem Elements

The series of charts contained in this section show the system design considerations and trade-offs used in conducting a spacecraft power system design and the design of the major components that make up the power system. These charts display the power system technology tasks that must be conducted in parallel with hardware technology development.

Figure 8 shows the integration of considerations necessary to conduct a power system design study. It starts with an analysis of system requirements and concludes with system technology documentation for advanced development and a definition of hardware technology requirements.

Figure 9 shows the solar array technology trade-offs. Note that aside from the power system and component technology there are major additional considerations that affect the technology outputs. These additional considerations include the broad areas of packaging, operations, and environment.

Figure 10 shows the design considerations and technology challenges to meet the life goal of 20 years for solar array actuators. Applicable technology may be from new advances in mechanisms, or it may be in the design of control circuitry.

Figure 11 shows the challenge of power distribution. The major technology challenge relates to voltage level, grounding, and techniques to transmit power across rotating joints.

Figure 12 shows the considerations of technology challenges to energy storage systems.

Conclusions

Current spacecraft are designed by an integrated analysis and systematic distribution of spacecraft resources. Power is one of the budgeted resources. If the available power can be increased at no increase in weight and a decrease in cost, total spacecraft performance improvement can be provided. Added calibration and temperature control could be provided that will improve the performance and life of the attitude control system. Increased power can simplify the complex electronic circuitry that is necessary for signal computation and conditioning. Additional power will improve design margins of electronics, and will redistribute spacecraft weight and performance.

The major technology challenges for space power systems for GEO are capacity 25-75 kw and life 20 years at minimum weight and affordable costs.

It is further forecasted that as a fallout of the above technology goals additional power will become available. This additional power will make a major impact on future communication spacecraft design and will stimulate a broad new companion ground based communication industry.

SPACECRAFT SYSTEMS

GOAL

- DEVELOP COST-EFFECTIVE OPERATIONAL SPACECRAFT AND SPACE OPERATIONS FOR THE 1990'S
  - INCREASE CAPABILITIES
  - DECREASE COSTS

FIGURE 1

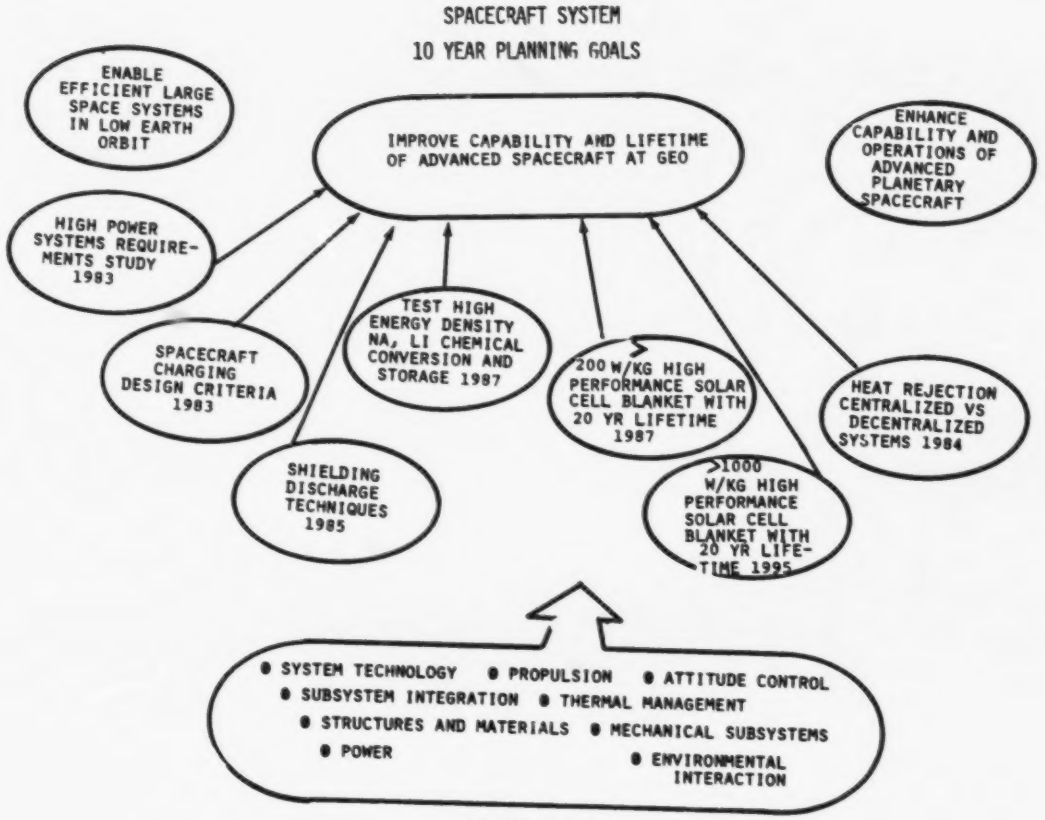
SPACECRAFT SYSTEM
10 YEAR PLANNING GOALS
ENABLE EFFICIENT LARGE SPACE SYSTEMS IN LOW EARTH ORBIT
IMPROVE CAPABILITY AND LIFETIME OF ADVANCED SPACECRAFT AT GEO
ENHANCE CAPABILITY AND OPERATIONS OF ADVANCED PLANETARY SPACECRAFT
HIGH POWER SYSTEMS REQUIREMENTS STUDY 1983
SPACECRAFT CHARGING DESIGN CRITERIA 1983
TEST HIGH ENERGY DENSITY NA, LI CHEMICAL CONVERSION AND STORAGE 1987
200 W/KG HIGH PERFORMANCE SOLAR CELL BLANKET WITH 20 YR LIFETIME 1987
HEAT REJECTION CENTRALIZED VS DECENTRALIZED SYSTEMS 1984
SHIELDING DISCHARGE TECHNIQUES 1985
>1000 W/KG HIGH PERFORMANCE SOLAR CELL BLANKET WITH 20 YR LIFETIME 1995
• SYSTEM TECHNOLOGY • PROPULSION • ATTITUDE CONTROL
• SUBSYSTEM INTEGRATION • THERMAL MANAGEMENT
• STRUCTURES AND MATERIALS • MECHANICAL SUBSYSTEMS
• POWER
• ENVIRONMENTAL INTERACTION

FIGURE 2

OAST SPACE SYSTEMS TECHNOLOGY MODEL
CHARACTERISTICS OF GEO SATELLITES AND PLATFORMS

MISSION NAME*	LAUNCH DATE	OBJECTIVE	SIZE (m)	MASS (kg)	LIFE (yr)	POWER** (kW)
STORMSAT (MESOSAT) (P)	1985	TO PREDICT ADVENT OF STORMS USING SPECTRAL SIGNATURES OF ATMOSPHERE			10	1 (H)
PUBLIC SERVICE COMMUNICATIONS SATELLITE (L)	1986	TO PROVIDE DIRECT DELIVERY OF HEALTH SERVICES, IMPROVED EDUCATIONAL, PUBLIC SERIVCES	60		10	5 (H)
GEOSTATIONARY PLATFORM (L)	1987	TO PROVIDE COMMUNICATION, OBSERVATION, NAVIGATION, SURVEILLANCE SERVICE	50	8,200	15	25 (M)
GLOBAL COMMUNICATIONS SYSTEM (L)	1987	TO PROVIDE INTERNATIONAL, PERSONAL COMMUNICATION; ELECTRONIC MAIL, TV BROADCASTS	50	30,000		150 (L)
DISASTER WARNING SYSTEM (L)	1988	TO DETECT ONSET OF FOREST FIRES, FLOODS, STORMS, INSECTS, ETC.	60	10,000		75 (L)
GLOBAL NAVIGATION SYSTEM (L)	1995	TO PROVIDE ACCURATE GEOLOCATION FOR INDIVIDUALS, VEHICLES	4 km	1,200		2 (H)
SATELLITE POWER SYSTEM (L)	2000+	TO CONVERT SOLAR ENERGY TO RF AND BEAM IT TO EARTH	20 km	10^8	30	5 GW (H)
SPACE BASED RADIO TELESCOPES (L)	1995	TO ENABLE INTERGALACTIC RESEARCH TO DETERMINE ORIGIN, DEFINITION OF UNIVERSE, SEARCH FOR EXTRA-TERRESTRIAL INTELLIGENCE	0.3 to 3 km	10^5	15	80 (L)

*MISSION STATUS: L, LONG RANGE; P, POSSIBLE

**CONFIDENCE LEVEL OF ESTIMATE: H, HIGH; M, MODERATE; L, LOW

FIGURE 3

OAST SPACE SYSTEMS TECHNOLOGY MODEL

CHARACTERISTICS OF GEO SATELLITES AND PLATFORMS

MISSION NAME*	LAUNCH DATE	SIZE (M)	MASS (KG)	LIFE (YR)	POWER** (KW)
C-7 NARROW BAND PROGRAM (O)	1988	-			2
C-4 GEOSTATIONARY PLATFORM DEMONSTRATION (P)	1990	80X30	5000-8000	8-10	25-40
C-3 30/20 GHZ ANTENNA WIDE BAND PROGRAM (P)	1986		1250		1-4
GPS (A/F)			-	5	
U-11 SPACE POWER TECHNOLOGY DEMO. (O)	TBD	5-10X10M ARRAYS			50
A-15 VERY LONG BASELINE RADIO INTERFEROMETER (C)	1990	30-60M, 1-22 GHZ, OUT TO 5000 KM		MINIMUM 3 YEARS	TBD (2 KW)

A - APPROVED, P - PLANNED, C - CANDIDATE, O - OPPORTUNITY

FIGURE 4

N80
33469

UNCLAS

WHAT DOES SYNCHRONOUS ORBIT MEAN TO SPACE POWER SYSTEM?

- o HOSTILE ENVIRONMENT
  - SPACECRAFT CHARGING, GROUNDING, SHIELDING
  - RADIATION COMPONENT DEGRADATION
- o REMOTE LOCATION
  - WEIGHT
    - o SOLAR ARRAY EFFICIENCY
    - o SYSTEM OPERATING VOLTAGE
    - o BATTERY CAPACITY AND DESIGN
    - o DESIGN ON END OF LIFE PERFORMANCE
  - 10 TO 20 YEAR LIFE
    - o COST OF REPAIR
    - o REDUNDANCY
    - o RELIABILITY
- o COST
  - DEVELOPMENT
    - o FUNDAMENTAL WORK ON MATERIALS, TECHNIQUES
  - DESIGN AND TEST
    - o INTEGRATION OF AUTOMATION FOR SELF MANAGEMENT WILL PROVIDE INTEGRATED SENSORS AND SWITCHING TO FACILITATE TEST
  - LAUNCH
    - o REDUCED WEIGHT
    - o REDUCED INTEGRATION TEST
  - MAINTENANCE AND REPAIR
    - o FAULT TOLERANT DESIGN TO MINIMIZE DEGRADATION
  - OPERATIONS
    - o AUTOMATION TECHNIQUES TO REDUCE CONTINUED DIRECT LABOR BY GROUND OPERATIONS
- o COMMUNICATION
  - 1000 BEAM
  - HIGH POWER
  - SHORT TERRESTRIAL TAILS
  - PROLIFERATED RECEIVERS
  - LOCATION (EAST OF U.S. TO OPTIMIZE SUN @ RIGHT FOR PEAK TRAFFIC U.S. TO EUROPE

FIGURE 5

WHAT DOES SYNCHRONOUS ORBIT MEAN TO SPACE POWER SYSTEM? (CONTINUED)

- o POWER SYSTEM CHARACTERISTICS
  - AVERAGE LOAD
    - o 1 KW OPERATIONAL
    - o 25 - 40 KW FORECAST NEED
    - o 75 KW CREATE NEW MARKETS AND IMPACT SPACECRAFT DESIGN
  - OPERATING LIFE
    - o 1 - 3 YEARS CURRENT CAPABILITY
    - o 1 - 5 YEARS CURRENT GOALS
    - o 1 - 10 YEARS CURRENT INCENTIVES
    - o 20 YEARS FORECAST
  - POWER SYSTEM 10 - 20% SPACECRAFT WEIGHT
    - o ARRAYS 35%
    - o BATTERIES 35%
    - o CONDITIONING AND REGULATION 8%
    - o DISTRIBUTION 22%
  - POWER ON ORBIT DEFINES
    - o SYSTEM CAPACITY IN BITS/SEC FREQUENCY
    - o GROUND ANTENNA SIZE AND COST
  - POWER USERS ON BOARD SPACECRAFT
    - o PAYLOAD
    - o DATA MANAGEMENT
    - o ATTITUDE CONTROL
    - o INSTRUMENTATION
    - o THERMAL MANAGEMENT
    - o COMMUNICATION
  - MORE POWER ON ORBIT AFFECTS
    - o ALL OTHER SPACECRAFT SUBSYSTEMS
    - o COST AND THEREFORE SIZE OF MARKET OF GROUND USERS

FIGURE 5 (CONT.)

IMPACT OF SURPLUS POWER ON SPACECRAFT DESIGN

- o IMPROVE PERFORMANCE
  - ADD CALIBRATION
  - ADD TEMPERATURE COMPENSATION
- o SIMPLIFY CIRCUITRY
  - IMPROVE REGULATION
- o IMPROVE RELIABILITY
  - INCREASE MARGIN
- o SIMPLIFY INTERFACES
- o REDISTRIBUTE BETWEEN SUBSYSTEMS
  - WEIGHT
  - PERFORMANCE
- o PROVIDE MORE SPACECRAFT SYSTEMS OPTIONS

FIGURE 6

FIRST ORDER ASSUMPTION OF EXPANDED COMMUNICATION MARKET

- o ASSUME SHORT TERRESTRIAL TAILS
- o ASSUME THE FOLLOWING LINK PARAMETERS
  - FREQUENCY 20 GHz
  - TERRESTRIAL DISK 0.6 M
  - TERRESTRIAL RECEIVER 300K
  - BANDWIDTH 100 MHz/BEAM
  - LOSS IN ATMOSPHERE 10^2
  - USER DATA RATE 10^5
- o ASSUME THE FOLLOWING MARKET
  - USERS 8×10^7
  - FRACTIONAL RECEIVER/TRANS/DAY 1.2×10^{-2}

  THEN TOTAL BIT FLOW IS
  - $8\ (10)^7 \times 1.2(10)^{-2} + (10)^5 = 10^{11}$
- o ASSUME A SATELLITE WITH
  - $(10)^3$ BEAMS
  - $(10)^3$ CHANNEL/BEAM
  - $(10)^5$ BIT/CHANNEL
  - 20 CHANNEL SIGNAL TO NOISE
- o SYSTEM COST SENSITIVITY TO QUANTITY OF RADIATED POWER

RF POWER	GROUND ANTENNA DIAMETER	POWER PLUS RF	ANTENNA (GROUND)	TOTAL
4.3 KW	(0.6M)	0.1	8	9.1
32 KW	(0.22M)	0.77	0.59	1.36

- o POWER GOALS
  - 100 KW SYSTEMS @ $100M
  - 10 YEAR OPERATION
  - PRODUCE ADDITIONAL UNIT EACH 2 1/2 YEARS

  OR
  - $10/KW HR.

FIGURE 7

FIRST ORDER ASSUMPTION OF EXPANDED COMMUNICATION MARKET (CONTINUED)

THIS GIVES A

- 163.2 DBW/M^2/Hz X 10^8

GIVES

- $163.2(10)^8$ $9(10)^{12}$ TOTAL RF POWER
  (43 KW TOTAL RF POWER ALL US)

TOTAL POWER ON BOARD

- $43(6) + 50 = 300$KW

IF YOU PAINT ONLY 10% OF US

TOTAL SATELLITE POWER $0.1\ (43)(6) + 50 = 75$KW

FIGURE 7 (CONT'D)

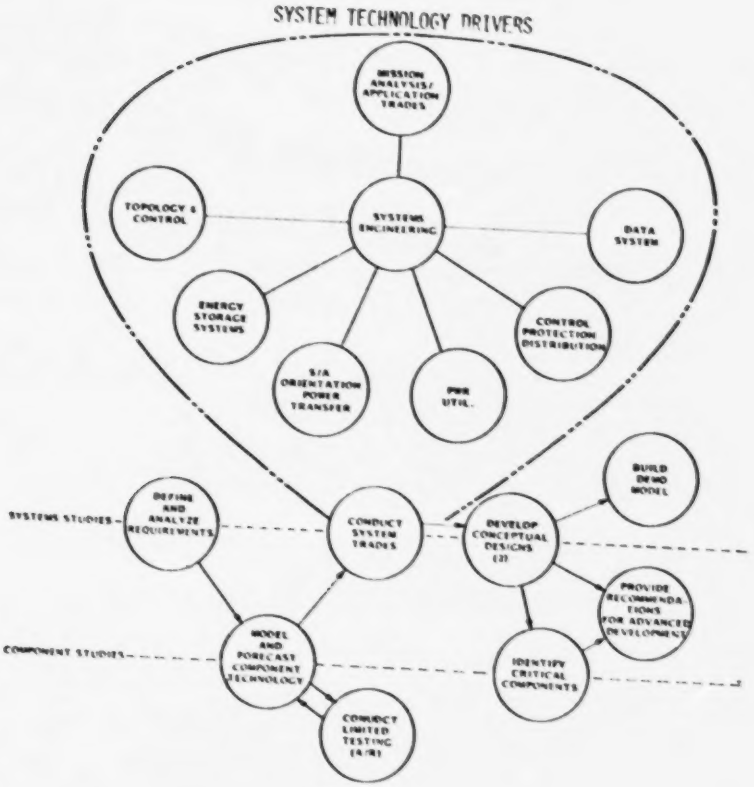

FIGURE 8

SOLAR ARRAY TECHNOLOGY TRADEOFFS

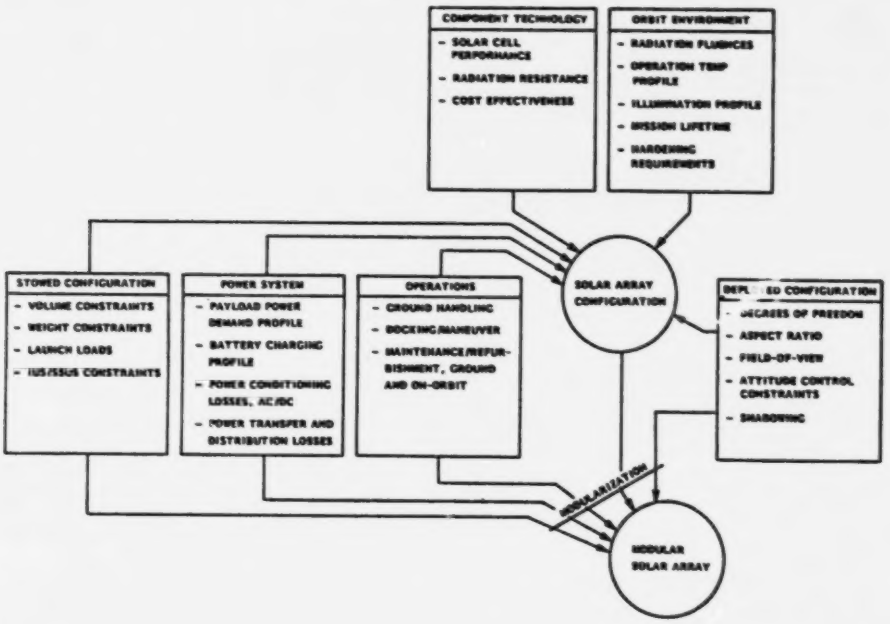

FIGURE 9

SOLAR ARRAY ACTUATOR

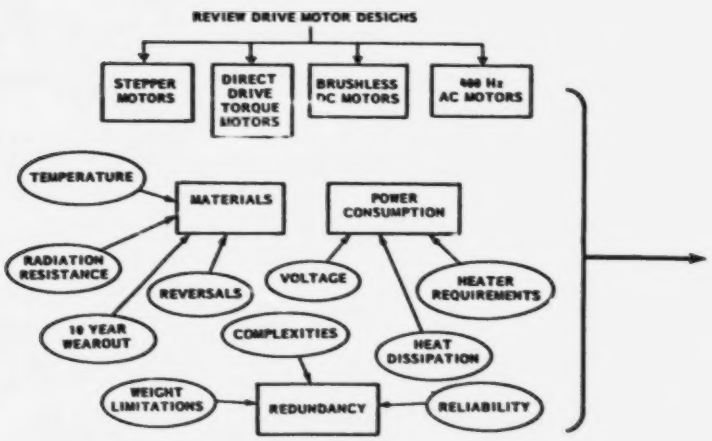

FIGURE 10

FIGURE 10 (CONT'D)

POWER TRANSFER TECHNOLOGY

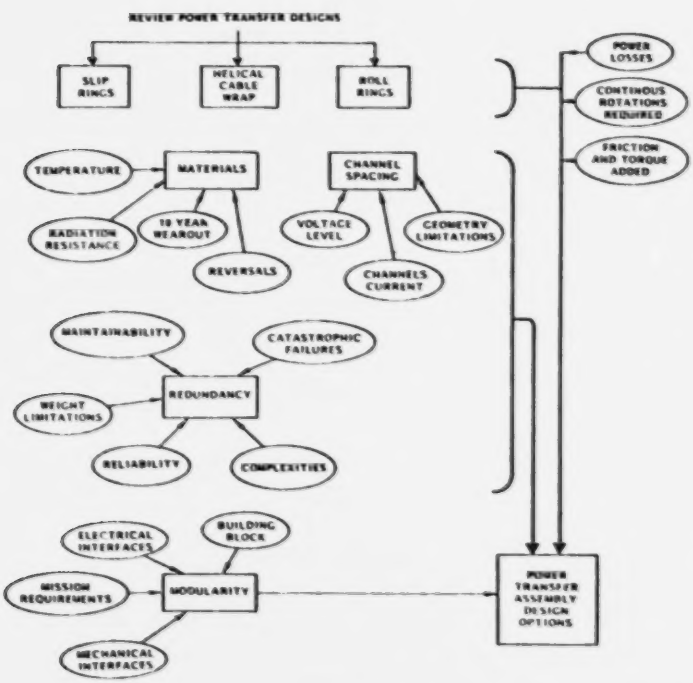

FIGURE 11

ENERGY STORAGE SYSTEM

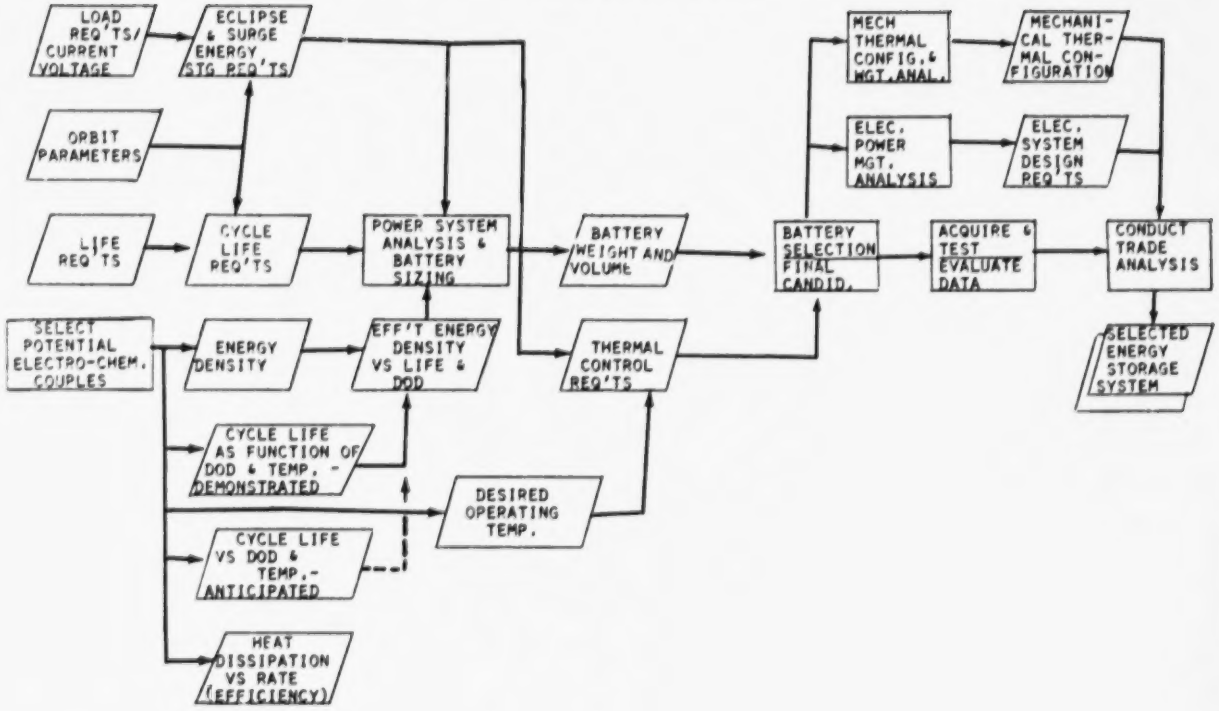
LOAD REQ'TS/ CURRENT VOLTAGE
ECLIPSE & SURGE ENERGY STG REQ'TS
ORBIT PARAMETERS
LIFE REQ'TS
CYCLE LIFE REQ'TS
POWER SYSTEM ANALYSIS & BATTERY SIZING
BATTERY WEIGHT AND VOLUME
MECH THERMAL CONFIG.& MGT.ANAL.
MECHANI-CAL THER-MAL CON-FIGURATION
ELEC. POWER MGT. ANALYSIS
ELEC. SYSTEM DESIGN REQ'TS
BATTERY SELECTION FINAL CANDID.
ACQUIRE & TEST EVALUATE DATA
CONDUCT TRADE ANALYSIS
SELECTED ENERGY STORAGE SYSTEM
SELECT POTENTIAL ELECTRO-CHEM. COUPLES
ENERGY DENSITY
EFF'T ENERGY DENSITY VS LIFE & DOD
THERMAL CONTROL REQ'TS
CYCLE LIFE AS FUNCTION OF DOD & TEMP. - DEMONSTRATED
DESIRED OPERATING TEMP.
CYCLE LIFE VS DOD & TEMP.- ANTICIPATED
HEAT DISSIPATION VS RATE (EFFICIENCY)

FIGURE 12

CONCLUSION

TECHNOLOGY MUST MOVE FORWARD TO PERMIT UP TO 20 YEAR LIFE IN THE GEOSYNCHRONOUS ORBIT ENVIRONMENT AT MINIMUM POWER LINK OF 25 - 40 KW FOR:

- MINIMUM WEIGHT
- AFFORDABLE COST

FIGURE 13

FORECAST

AS A FALL OUT OF THE TECHNOLOGY REQUIREMENTS JUST STATED, ADDITIONAL POWER WILL BE AVAILABLE THAT WILL:

- MAKE A MAJOR IMPACT ON FUTURE SPACECRAFT DESIGN
- STIMULATE BROAD NEW COMPANION GROUND BASED COMMUNICATION INDUSTRIES

FIGURE 14

D5

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PHOTOVOLTAIC TECHNOLOGY DEVELOPMENT FOR SYNCHRONOUS ORBIT

Henry W. Brandhorst
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

SOLAR CELL TECHNOLOGY - 18% SILICON CELL DEVELOPMENT

TARGET: ACHIEVE SILICON SOLAR CELL EFFICIENCY OF 18% AT 200 TO 250 MICROMETER THICKNESS BY END OF FY 1981

EXPECTED BENEFIT:

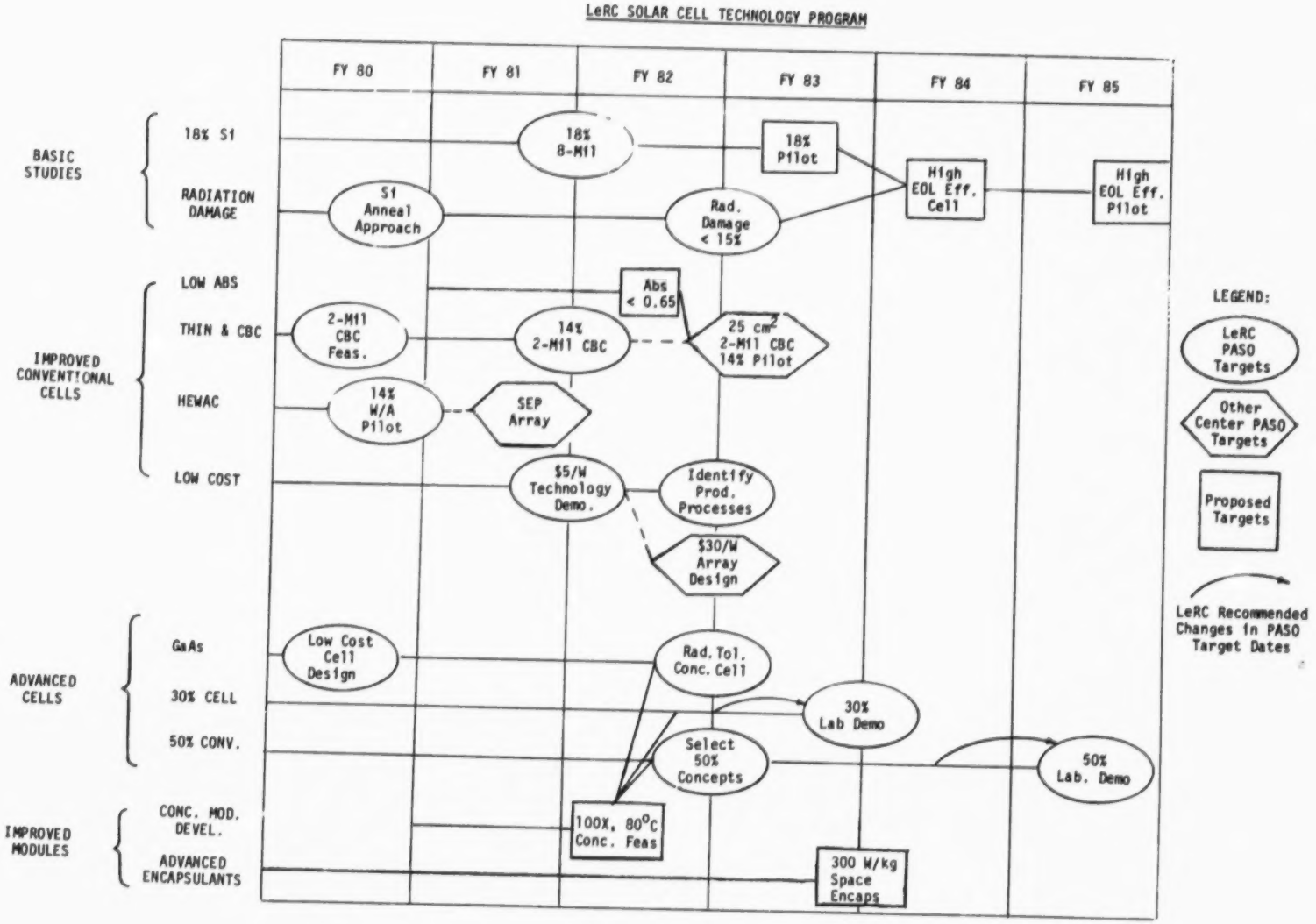
- YIELDS A CELL WITH 20% MORE OUTPUT THAN THOSE CURRENTLY AVAILABLE.

FY '80 ACCOMPLISHMENTS:

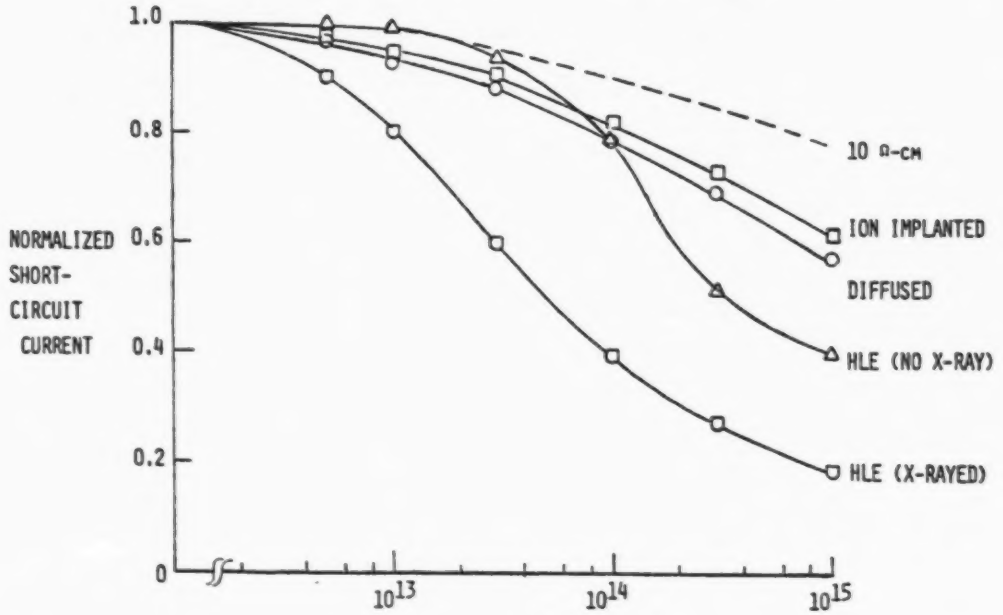
- ACHIEVED OPEN-CIRCUIT VOLTAGES OF 645 mV IN 0.1 OHM-CM CELLS.
- DETERMINED THAT BASE REGION CONTROLS DIFFUSED AND ION IMPLANTED CELLS, EMITTER CONTROLS HIGH-LOW EMITTER (HLE) CELL.
- SHOWED THAT THE HLE CELL IS MORE SENSITIVE TO 1 MeV ELECTRONS THAN OTHER DESIGNS AND HAVE PROPOSED DESIGN CHANGES BASED ON THEORETICAL MODELING.
- AWARDED CONTRACT TO DEVELOP 18% SILICON CELL.

FY '81 PLANS:

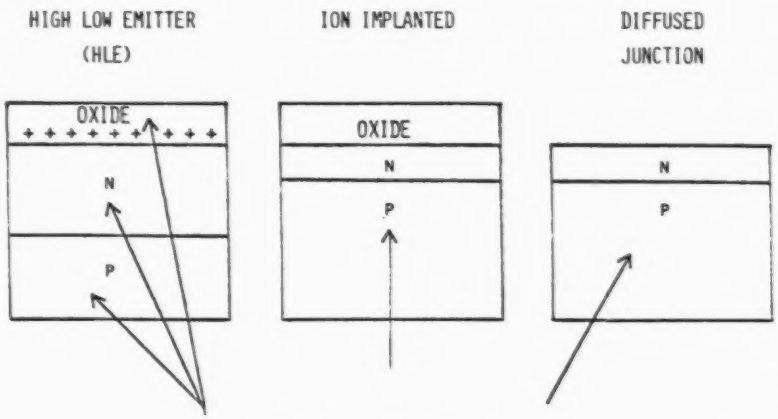
- VERIFY AND CONTROL VOLTAGE LIMITING MECHANISMS.
- THROUGH CONTRACT AND IN-HOUSE EFFORTS PRODUCE 700 mV VOLTAGE AT 44 mA/cm^2 CURRENT DENSITY AND 18% CELL BY END OF FY 1981.


LeRC SOLAR CELL TECHNOLOGY PROGRAM
FY 80
FY 81
FY 82
FY 83
FY 84
FY 85
BASIC STUDIES
18% S1
RADIATION DAMAGE
IMPROVED CONVENTIONAL CELLS
LOW ABS
THIN & CBC
HEWAC
LOW COST
ADVANCED CELLS
GaAs
30% CELL
50% CONV.
IMPROVED MODULES
CONC. MOD. DEVEL.
ADVANCED ENCAPSULANTS
18% 8-Mil
18% Pilot
High EOL Eff. Cell
High EOL Eff. Pilot
S1 Anneal Approach
Rad. Damage < 15%
Abs < 0.65
2-Mil CBC Feas.
14% 2-Mil CBC
25 cm² 2-Mil CBC 14% Pilot
14% W/A Pilot
SEP Array
$5/W Technology Demo.
Identify Prod. Processes
$30/W Array Design
Low Cost Cell Design
Rad. Tol. Conc. Cell
30% Lab Demo
Select 50% Concepts
50% Lab. Demo
100X, 80°C Conc. Feas
300 W/kg Space Encaps
LEGEND:
LeRC PASO Targets
Other Center PASO Targets
Proposed Targets
LeRC Recommended Changes in PASO Target Dates

EFFECT OF 1 MeV ELECTRONS ON CELLS WITH IMPROVED OPEN-CIRCUIT VOLTAGE



SOURCES OF RADIATION INDUCED DEGRADATION IN HIGH VOLTAGE SILICON SOLAR CELLS



REGIONS WHERE RADIATION DEGRADES CELL PERFORMANCE

SOLAR CELL TECHNOLOGY - RADIATION DAMAGE

TARGET: DEMONSTRATE TECHNOLOGY FOR REDUCING SILICON CELL RADIATION DAMAGE IN SYNCHRONOUS EARTH ORBIT AFTER TEN YEARS TO LESS THAN 15% BY THE END OF 1982

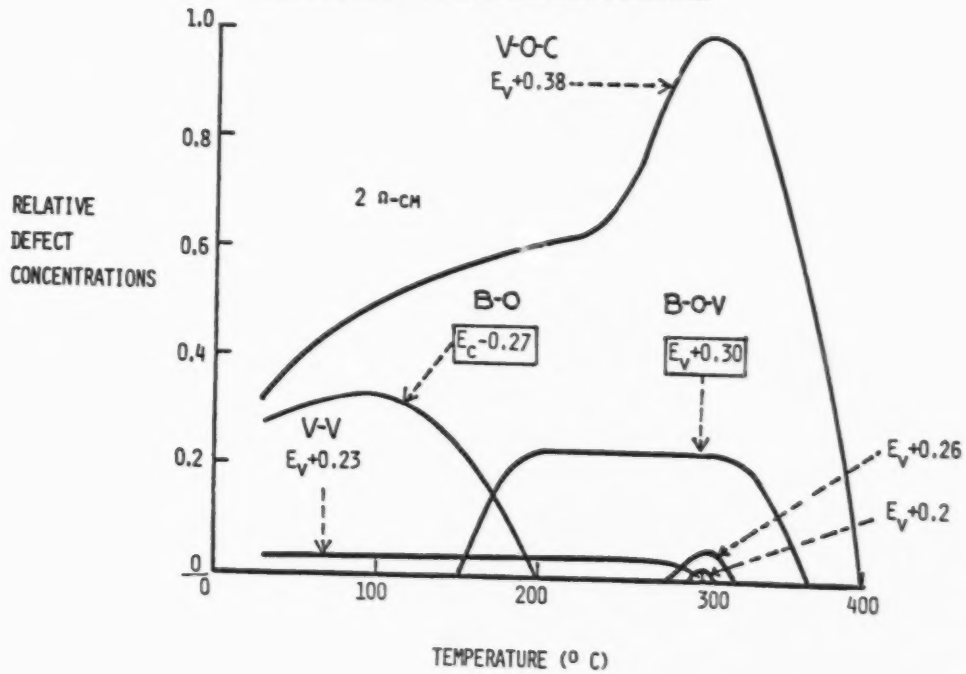
EXPECTED BENEFIT:

- YIELDS UP TO 25% IMPROVEMENT IN POWER OUTPUT AFTER 1 YEAR IN SYNCHRONOUS EARTH ORBIT.

FY '80 ACCOMPLISHMENTS:

- IDENTIFIED THE DEFECT (B-O-V) RESPONSIBLE FOR REVERSE ANNEALING IN 2 OHM-CM CELLS.
- DEMONSTRATED THAT LITHIUM COUNTERDOPED 0.1 OHM-CM CELLS ANNEAL AT ROOM TEMPERATURE AND SHOW LESS INITIAL DEGRADATION THAN CELLS WITHOUT LITHIUM.
- DEVELOPED IMPROVED TECHNIQUE FOR DETECTING OXYGEN IN SILICON.
- SHOWED THAT REDUCTION OF BORON, CARBON AND OXYGEN IMPROVES RADIATION TOLERANCE.

RADIATION INDUCED DEFECTS IN P-TYPE SILICON



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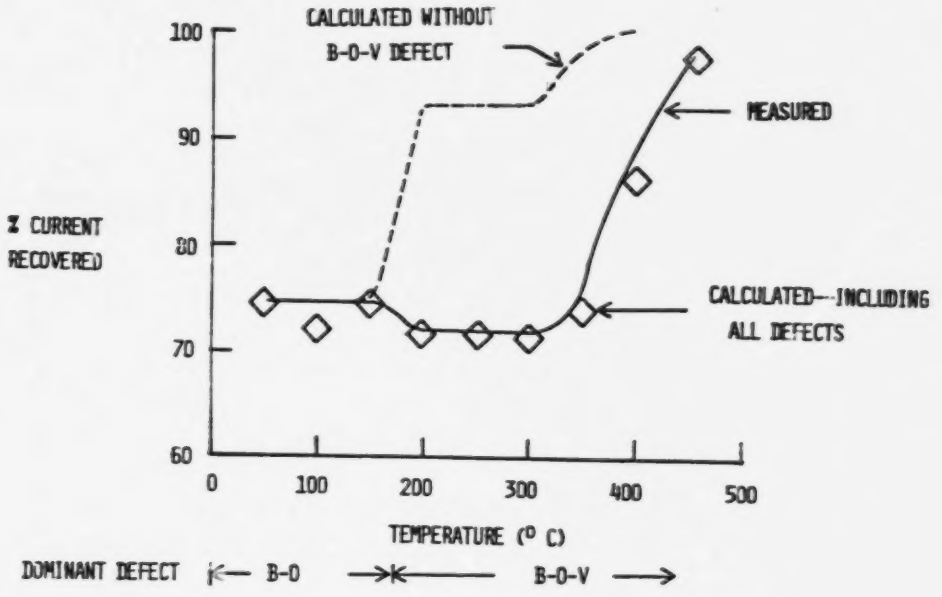
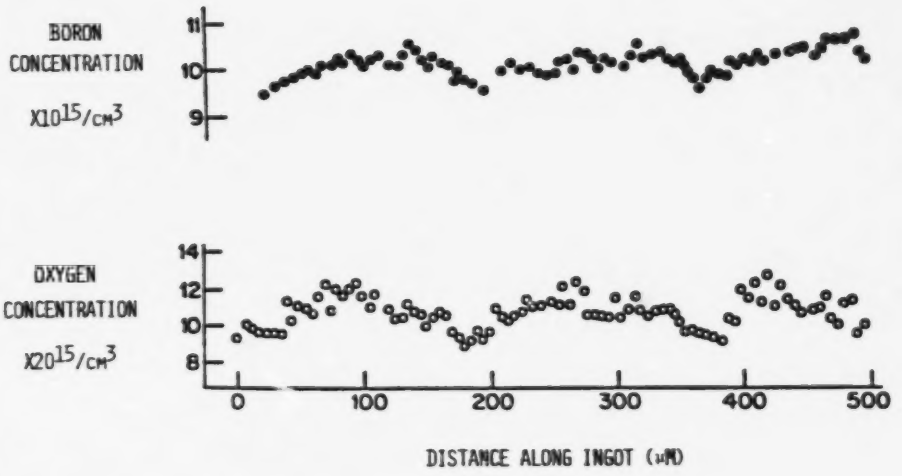
RECOVERY OF RADIATION DAMAGE SOLAR CELL CURRENT BY ANNEALING



DISTRIBUTION OF OXYGEN AND BORON IN CZOCHRALSKI
GROWN SINGLE CRYSTAL SILICON
(MIT - NSG 3017)



SOLAR CELL TECHNOLOGY COPLANAR BACK CONTACT CELLS

TARGET: DEMONSTRATE COPLANAR BACK CONTACT 50 μm THICK SILICON SOLAR CELLS WITH EFFICIENCIES OF 14% BY THE END OF FY 1981

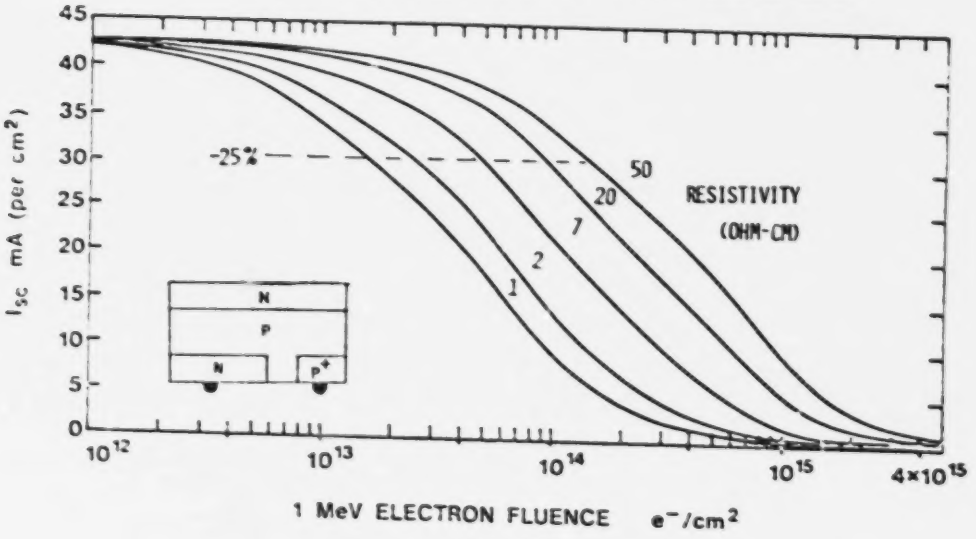
EXPECTED BENEFIT:

- INCREASES CAPABILITY OF SEP MISSION BY 10-25%.

FY '80 ACCOMPLISHMENTS:

- DEMONSTRATED 13% INTERDIGITATED BACK CONTACT (IBC) CELL.
- CALCULATED PERFORMANCE OF IBC CELLS WHICH INDICATED THEIR INCREASED SENSITIVITY TO RADIATION DAMAGE COMPARED TO A FRONT JUNCTION DEVICE.
- DEMONSTRATED REDUCTIONS IN CELL ABSORPTIVITY USING IMPROVED BACK-SURFACE REFLECTORS THAT WOULD LEAD TO IN-ORBIT TEMPERATURES 15° C LOWER THAN PRESENT CELLS.
- DEMONSTRATED HEWAC CELL YIELDS ABOVE 60% OF CELLS WITH EFFICIENCIES ABOVE 14% AND HAVE RECONFIGURED CONTACT TO FIT SEP AND USAF REQUIREMENTS.

CALCULATED PERFORMANCE OF 100 μm TANDEM JUNCTION CELLS



OAST THIN CELL DEVELOPMENT

- o VOLUME PRODUCTION DEMONSTRATED 10,000/MONTH.
- o AVERAGE POWER ~ 16.5 mW/cm^2.
- o HIGHEST ABSOLUTE POWER OUTPUT OF ANY SILICON SOLAR CELL AFTER $1x10^{15}$ e/cm^2 (1 MeV).
- o ADVANCED OAST THIN CELLS (> 17.5 mW/cm^2) AVAILABLE FROM SPACE QUALIFIED SOURCES.

SOLAR CELL TECHNOLOGY - GaAs CELL DEVELOPMENT

TARGET: DEMONSTRATE FEASIBILITY OF A RADIATION TOLERANT GaAs CONCENTRATOR CELL IN FY 1982

EXPECTED BENEFIT:

- A RADIATION INSENSITIVE, ANNEALABLE ARRAY WITH POTENTIAL FOR COSTS EQUIVALENT TO SILICON.

FY '80 ACCOMPLISHMENTS:

- DEMONSTRATED 16% EFFICIENT, 2x2 CM, CVD, N/P GaAs SOLAR CELL WITH RADIATION DEGRADATION OF ABOUT 12% AFTER 10 YEARS IN GEO.
- AWARDED CONTRACT TO DEVELOP 5 CM DIAMETER CZOCHRALSKI-GROWN GaAs CRYSTALS WITH LOW BACKGROUND IMPURITY CONCENTRATION AND LOW DISLOCATION DENSITY.
- ISSUED RFP TO DEVELOP A CONCENTRATOR GaAs CELL WITH POTENTIAL FOR 200^{o} C OPERATION.

NASA - LANGLEY RESEARCH CENTER

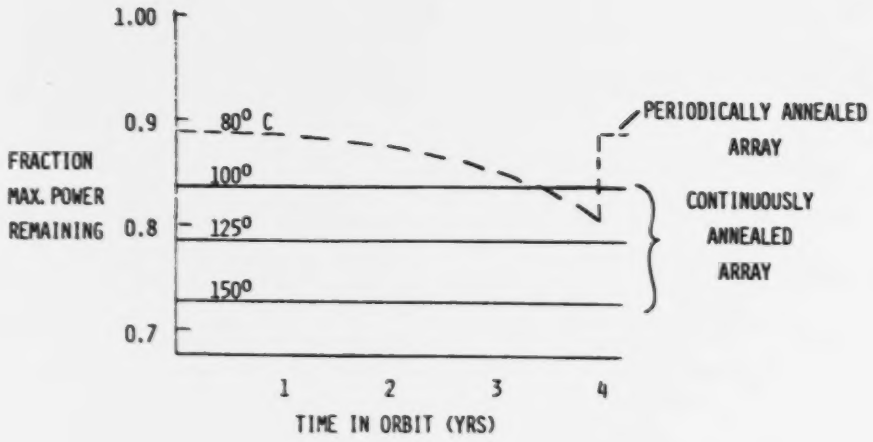
THERMAL ANNEALING OF RADIATION DAMAGE TO GaAs SOLAR CELLS

(1) CONTINUED WORK ON KINETIC PARAMETERS SUCH AS ACTIVATION ENERGY AND FREQUENCY FACTORS (DEFINED AN ANNEALING STAGE NEAR 200C).

(2) IF CELLS ARE OPERATED CONTINUOUSLY AT TEMPERATURES BETWEEN 120 AND 150C, THE SLOW BUT CONTINUOUS ANNEALING THAT RESULTS MAY BE SUFFICIENT TO ALLEVIATE THE EFFECTS OF SPACE RADIATION ON CELL CONVERSION EFFICIENCY.

(3) IF ANNEALING OF PROTON DAMAGE IS EFFECTIVE, OPERATION WITHOUT A COVER GLASS RADIATION SHIELD MAY BE PRACTICAL. THUS THE CELL POWER-TO-WEIGHT RATIO WOULD BE SIGNIFICANTLY IMPROVED AND CELL CONSTRUCTION WOULD BE SIMPLIFIED. THE CELL STABILITY WOULD ALSO IMPROVE, SINCE A COVER GLASS ADHESIVE WOULD NO LONGER BE NECESSARY.

EFFECT OF PERIODIC ANNEALING ON ARRAY OUTPUT
COMPARED TO CONTINUOUS ANNEALING
AT HIGHER TEMPERATURE
GaAs CELLS



CONCENTRATOR ENHANCED ARRAY DEVELOPMENT

- o SPECIFIC POWER IMPROVEMENT MARGINAL.
- o OBVIOUS COST BENEFITS.
- o GaAs IS LIKELY CANDIDATE FOR GEO APPLICATIONS.
- o $C_G \sim 3\text{-}7$ NEEDED FOR GEO.

SOLAR CELL TECHNOLOGY - 30% CELL

TARGET: ACHIEVE 30% EFFICIENT PHOTOVOLTAIC CONVERSION IN THE LABORATORY BY THE END OF FY 1983

EXPECTED BENEFITS:

- DOUBLES POWER DENSITY OF ARRAYS; CUTS ARRAY SIZE IN HALF.

FY '80 ACCOMPLISHMENTS:

- CALCULATIONS INDICATE THAT 100X CONCENTRATION AND 80° C TEMPERATURES ARE REQUIRED TO ACHIEVE 30% EFFICIENCY IN A THREE JUNCTION GaAlAsSb CASCADE CELL.
- TUNNEL JUNCTION RESISTANCE A KEY PROBLEM, MAY LIMIT CASCADE STRUCTURES TO LESS THAN FOUR TANDEM JUNCTIONS.

FY '81 PLANS:

- CONTRACT FOR EXPERIMENTAL DEVELOPMENT OF POTENTIAL 30%, 100X CONCENTRATION LEVEL CELL.
- DETERMINE TRADEOFFS BETWEEN TUNNEL JUNCTION RESISTANCE, CONCENTRATION RATIO, CELL AND SIZE AND OPERATING TEMPERATURE.

SOLAR CELL TECHNOLOGY - 50% CONVERSION

TARGET: DEFINE CANDIDATE CONCEPTS FOR 50% EFFICIENT ELECTROMAGNETIC CONVERSION BY FY 1982

EXPECTED BENEFIT:

- TRIPLES POWER OUTPUT OF ARRAYS AND REVOLUTIONIZES SOLAR ENERGY CONVERSION BOTH IN SPACE AND TERRESTRIALLY.

FY '80 ACCOMPLISHMENTS:

- EXPLORING POTENTIAL OF WAVE NATURE OF LIGHT COMBINED WITH MICROMINIATURE STRUCTURES TO ACHIEVE HIGH CONVERSION EFFICIENCY.
- DEVELOPING MODELS DESCRIBING THE COHERENCE PROPERTIES OF SUNLIGHT.
- CONTRACTOR INDICATES THAT TUNNEL JUNCTION RESISTANCE MAY PRECLUDE 50% EFFICIENCY FOR STACKED JUNCTIONS.

FY '81 PLANS:

- CONTINUE 50% MODEL DEVELOPMENT IN-HOUSE AND ON GRANT.
- SEEK TO IDENTIFY POSSIBLE APPROACHES THAT MAY LEAD TO 50% CONVERSION.

SOLAR CELL TECHNOLOGY - ADVANCED ENCAPSULANTS

NEW TARGET: DEMONSTRATE TECHNOLOGY FOR PROTECTING ARRAYS CAPABLE OF > 300 W/KG AFTER 10 YEARS IN GEO BY END OF FY 1983

EXPECTED BENEFIT:

- SUBSTANTIALLY REDUCED COSTS AND INCREASED POWER TO WEIGHT RATIOS OF SPACE ARRAYS.

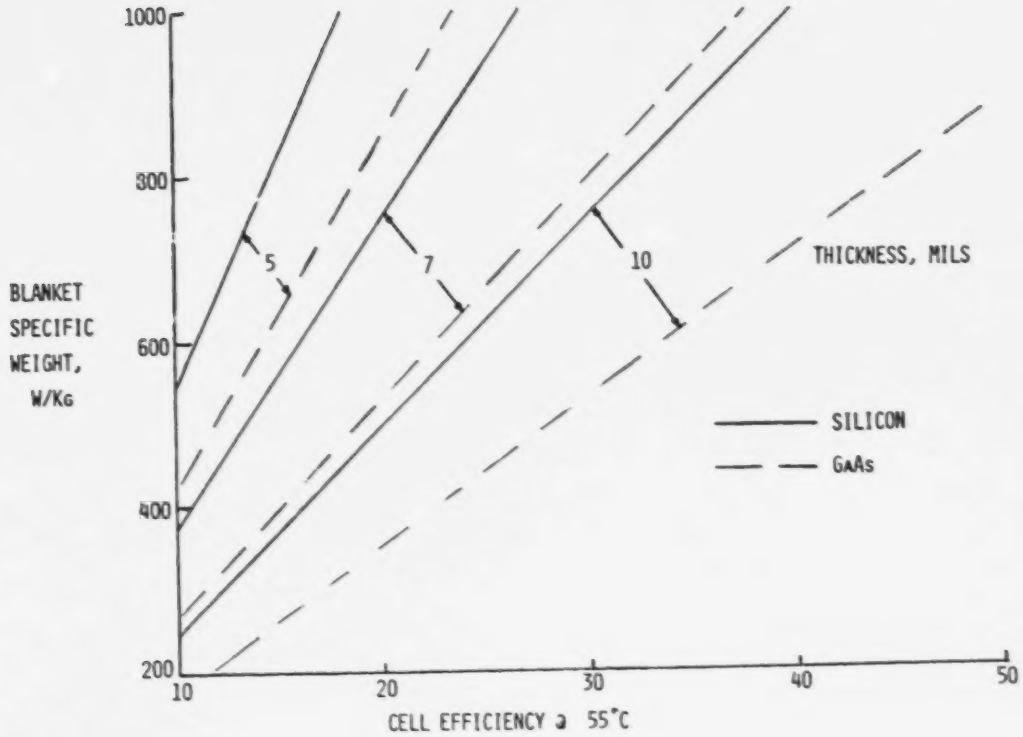
FY '80 ACCOMPLISHMENTS:

- AWARDED CONTRACT TO DEVELOP TECHNIQUE FOR ELECTROSTATIC BONDING OF 50 μM GLASS TO 50 μM CELLS. INTEGRATED CURRENT DURING BONDING IMPORTANT.
- AWARDED CONTRACT FOR TESTING ENCAPSULATED CELLS IN A SPACE ENVIRONMENT (PARTICULATE AND ULTRAVIOLET).
- DEMONSTRATED SINGLE CELL PACKAGE YIELDING 350 W/KG - 50 μM CELL, 75 μM ADHESIVE BONDED COVER AND 25 μM KAPTON BACKING.

THIN CELL BLANKET DEVELOPMENT

- o LAYDOWN AND INTERCONNECT FEASIBILITY DEMONSTRATED - 1977.
- o 75 μM GLASS COVERED CELL MODULES DEMONSTRATED - 1979.
- o PRODUCTION PROCESSES NOW BEING DEVELOPED.
  - TEFLON BONDED COVERS
  - OAST CELLS FROM 3 SOURCES
  - 50 μM MICROSHEET COVERS
  - IN-PLANE INTERCONNECT
- o 2000 CELL DEMONSTRATION BLANKET TO BE FABRICATED IN 1981.
- o SPECIFIC POWER > 250 W/KG ANTICIPATED.

ADVANCED BLANKET TECHNOLOGY REQUIREMENTS



PLANETARY SOLAR ARRAY RESEARCH & TECHNOLOGY

APPROACH

- o GaAs (GALICON) SOLAR CELL DEVELOPMENT
  - o > 18% EFFICIENT, 50 μM THICK
- o CELL EVALUTION AND RADIATION EFFECTS ANALYSIS
  - o RADIATION DAMAGE ANNEALING
- o OAST 50 μM THIN SILICON CELL DEVELOPMENT
  - o PILOT LINE
  - o 2 x 2 CM, > 13% EFFICIENT
  - o 5 x 5 CM, > 12% EFFICIENT
- o HIGH PERFORMANCE BLANKET DEVELOPMENT
  - o > 240 W/KG
- o CONCENTRATOR ENHANCED ARRAY DEVELOPMENT
  - o GEOSYNCHRONOUS MISSIONS, 300 W/KG
  - o OUTBOUND MISSIONS, ENABLING TECHNOLOGY 5 TO 10 AU

N80-33471

LARGE SOLAR ARRAYS

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Marshall Space Flight Center
National Aeronautics and Space Administration
Huntsville, Alabama

MULTIHUNDRED kW SOLAR ARRAYS FOR EARTH ORBIT

The objective of the multihundred program is to evaluate a broad range of concepts for reducing the cost of photovoltaic energy in space. In order to provide a focus for the effort, an orbital power platform mission in the late 80's is being used to allow a coherent technology advancement program.

Specific Objective:

- Evaluate a broad range of advanced concepts for reducing cost of photovoltaic energy

Targets:

- Evaluate alternative approaches and produce technology development plans for the most promising by mid FY 1981.
- Complete planar array low cost blanket evaluation in FY 1982.
- Demonstrate low energy cost modules by end of FY 1982.
- Demonstrate low energy cost photovoltaic systems by end of FY 1984.

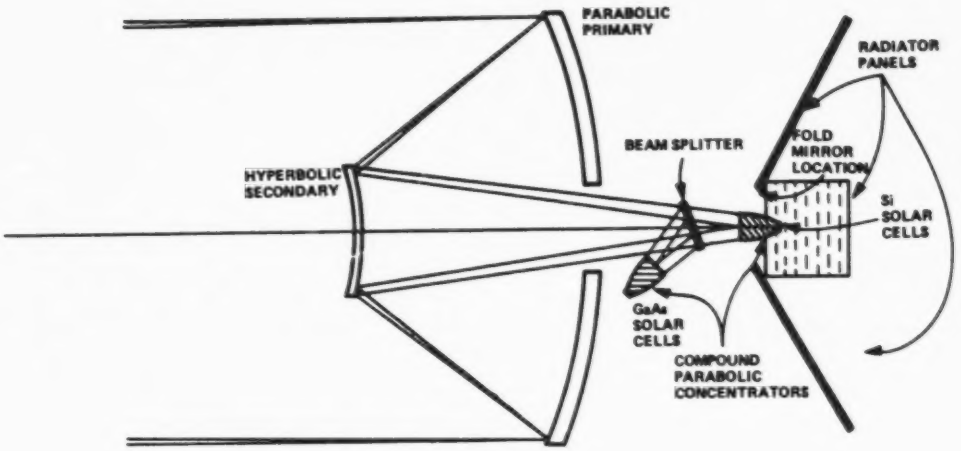
*(Ten year life with maintenance at a captial recurring cost of $30/watt based on 1978 dollars)

ARRAY CONCEPTS

In keeping with the objective of evaluating a broad range of concepts, shown below are five array concepts that are being investigated. These invovle a range of technology risks. The high risk technology is represented by thermophotovoltaics and spectrophotovoltaics. Each of these involves manipulation of the incoming spectrum to enhance the system efficiency, but have several unanswered technology questions, resulting in an unknown potential payback. The lowest technology risk is represented by the planar array, which has no technology risk and a moderate payback. In between the high and low risk technologies are the cassagrainian and high flux approaches.

TASKS	PRIMARY CHARACTERISTIC	TECHNOLOGY RISK	POTENTIAL PAYBACK
●SPECTROPHOTOVOLTAICS	BEAM SPLITTING	HIGH	UNKNOWN
●THERMOPHOTOVOLTAICS	SPECTRAL SHIFTING	HIGH	UNKNOWN
●CASSEGRAINIAN CONCENTRATOR	HIGH CR	MODERATE	HIGH
●HIGH FLUX	LOW CR	LOW	MODERATE
●LARGE SILICON CELL BLANKET	PLANAR	NONE	LOW TO MODERATE

FINAL OPTICAL SYSTEM DESIGN SCHEMATIC

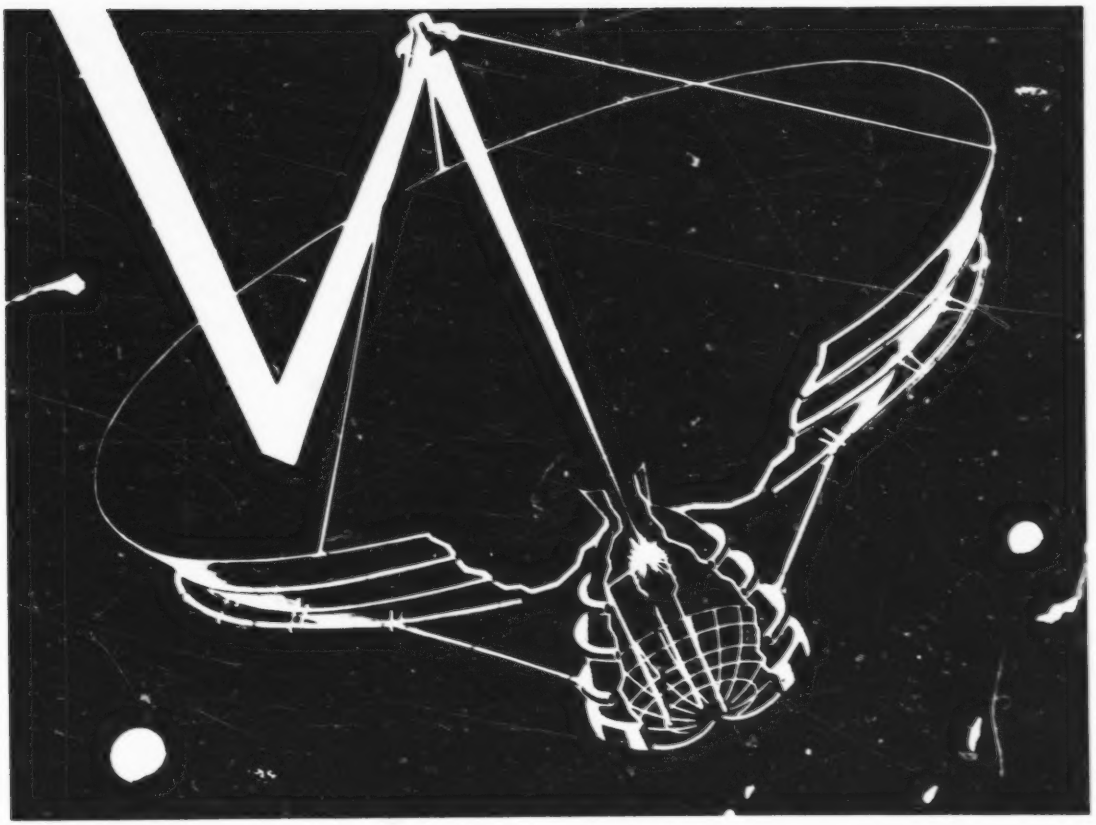


SPECTROPHOTOVOLTAIC CONVERTER

In consists of a primary parabolic mirror and a hyperbolic secondary mirror which concentrate the sunlight. The light then passes through a beam splitter (dichroic mirror) or a number of beam splitters depending upon the design. The beam splitter splits the spectrum, sending a portion of it to a solar cell which is designed to convert the energy in that spectral region and the remainder of the spectrum is passed, eventually either being split again or going intact to another solar cell. In the particular concept shown, one beam splitter is used to split the spectrum sending part of it to a GaAs solar cell and passing the remainder to a silicon cell. The concept shown also uses compound parabolic concentrators at the cell as well as radiator panels for thermal dissipation. Of particular concern with spectrophotovoltaic converters is the tradeoff between efficiency and the number of cells required since the cost of developing new cells is generally prohibitive. Another major technology concern is spectrophotovoltaic converter sizing which has an impact on concentrator development, radiator weight, packaging and the maintainability philosophy, all of which are legitimate technology concerns in their own right.

SPECTROPHOTOVOLTAIC CONVERTER

- TECHNOLOGY NEED:
  LOW COST HIGH PERFORMANCE SOLAR ARRAYS IN LATE 80's
- CONVERTER COMPONENTS
  - CONCENTRATORS - CASSEGRAINIAN AND CPC
  - BEAM SPLITTER - DICHROIC MIRROR
  - SOLAR CELL - SILICON AND GaAs
  - HEAT REJECTION - RADIATOR
- TECHNOLOGY CONCERNS
  - CELL DEVELOPMENT
  - CONCENTRATOR DEVELOPMENT
  - MODULE SIZING
  - MAINTAINABILITY PHILOSOPHY
  - RADIATOR WEIGHT
  - PACKAGING



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THERMOPHOTOVOLTAIC CONVERTER

A thermophotovoltaic converter operates as follows: Solar energy is collected and focused on a "black body" absorber within a cavity. The absorbed energy is re-emitted from the converter with a 3000 K "black body" spectrum. The inside of the cavity is covered with solar cells which are irradiated with the 3000 K spectrum energy. Ideally the cells convert the energy in the 0.5 to 1.0 μ wavelength band into electricity and reflect the energy at wavelengths greater than 1.0 μ back to the "black body" where it is absorbed and then re-emitted with the 3000 K spectrum. The overall result is that the incoming spectrum is shifted to one which the solar cell would rather see.

The thermophotovoltaic converter has technology questions in the same areas as the spectrophotovoltaic converter although the concerns themselves are different. Major ones are briefly as follows: What size should the converter be? Can existing cells and concentrators be used or is cell and concentrator development required? Will radiator weight be prohibitive? Can the converter or a sufficient number of converters be packaged in the space shuttle? And what should be the maintainability philosophy?

THERMOPHOTOVOLTAIC CONVERTER

- TECHNOLOGY NEED
  - LOW COST HIGH PERFORMANCE SOLAR ARRAYS IN LATE 80's
- CONVERTER COMPONENTS
  - CONCENTRATOR - CASSEGRAINIAN
  - CAVITY - PORTION OF A SPHERE
  - ABSORBER - TUNGSTEN
  - SOLAR CELL - SILICON
  - HEAT REJECTION - RADIATOR
- TECHNOLOGY CONCERNS
  - CELL DEVELOPMENT
  - CONCENTRATOR DEVELOPMENT
  - MODULE SIZING
  - MAINTAINABILITY PHILOSOPHY
  - RADIATOR WEIGHT
  - PACKAGING

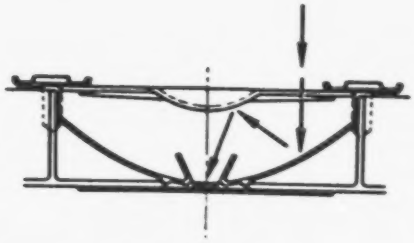
CASSEGRAINIAN CONCENTRATOR

Below is shown a sketch of a cassegrainian concentrator concept for a multihundred kW solar array application.

The cassegrainian concept shown would make up an array which would deploy as a planar array and would provide 940 kW per shuttle launch using an advanced concentrator solar cell. It uses a concentration ratio of 125.

500 kW† MINIATURIZED CASSEGRAINIAN CONCEPT

STUDY OF MULTI-kW SOLAR ARRAYS
FOR EARTH ORBIT APPLICATIONS
NAS8-32986



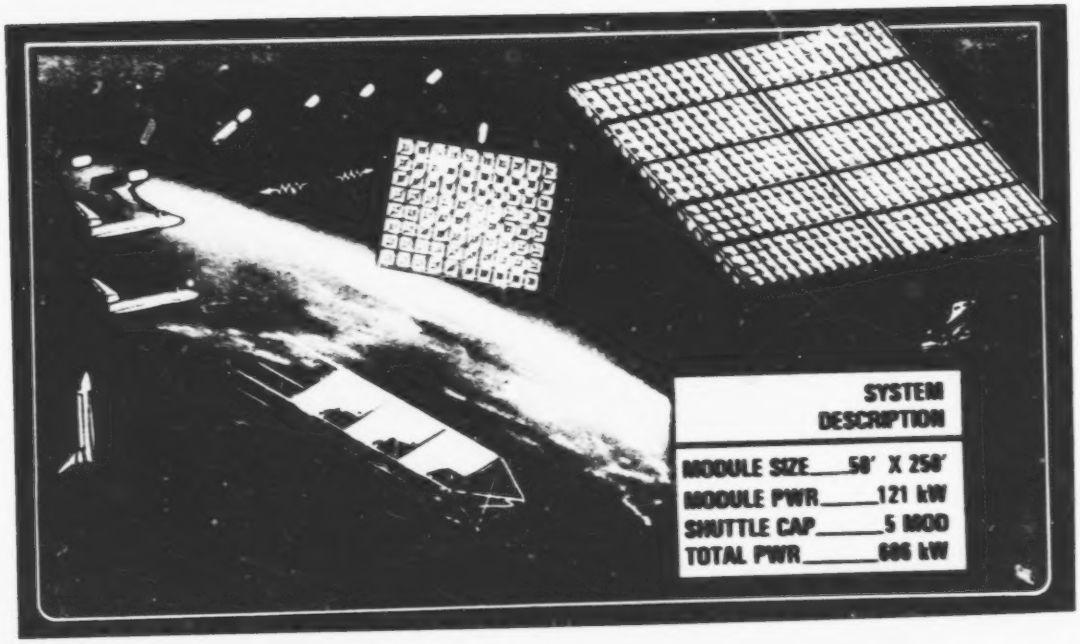
- 12 mm THICK PANELS OF CONCENTRATORS DEPLOY AND OPERATE IDENTICALLY TO PLANAR ARRAY CONCEPT
- FOLDING MIRROR SYSTEM UNIFORMLY ILLUMINATES 4 x 4 mm CELL AT 125 SUN INTENSITY
- CONE-TERTIARY REFLECTOR PROVIDES OFF-POINTED CAPABILITY TO ~4 DEGREES TO ACCOMMODATE MISALIGNMENT AND FIGURE CONTROL
- CELLS COUPLED TO PASSIVE RADIATORS
- 15*W/kg, 75*W/m^2, 325* - 500** kW/LAUNCH
- MAINTENANCE AT 1 kW LEVEL BY EVA AND WITH AN ON-ORBIT STORAGE OPTION

† PER ORBITER LAUNCH

* BASED ON 12% CELL EFFICIENCY AT 100°C

** 18% GaAs CELL

LOW-CR CONCENTRATOR CONCEPT



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HIGH FLUX CONCENTRATOR

The high flux concentrator concept shown in the previous artist's concept is known as a truncated pentrahedral concept. Its basic building block is a five faced figure with four reflectors arranged to form a rectangle with the reflectors tilted to reflect the sunlight into the bottom of the rectangle which contains solar cells.

The concept is capable of providing a total beginning of life power of 606 kW with one shuttle launch by carrying five (5) modules (module power 121 kW, module dimensions 50 ft × 250 ft) the concept has a geometric CR of 5 and can utilite silicon or GaAs solar cells. (The power numbers are for GaAs cells.)

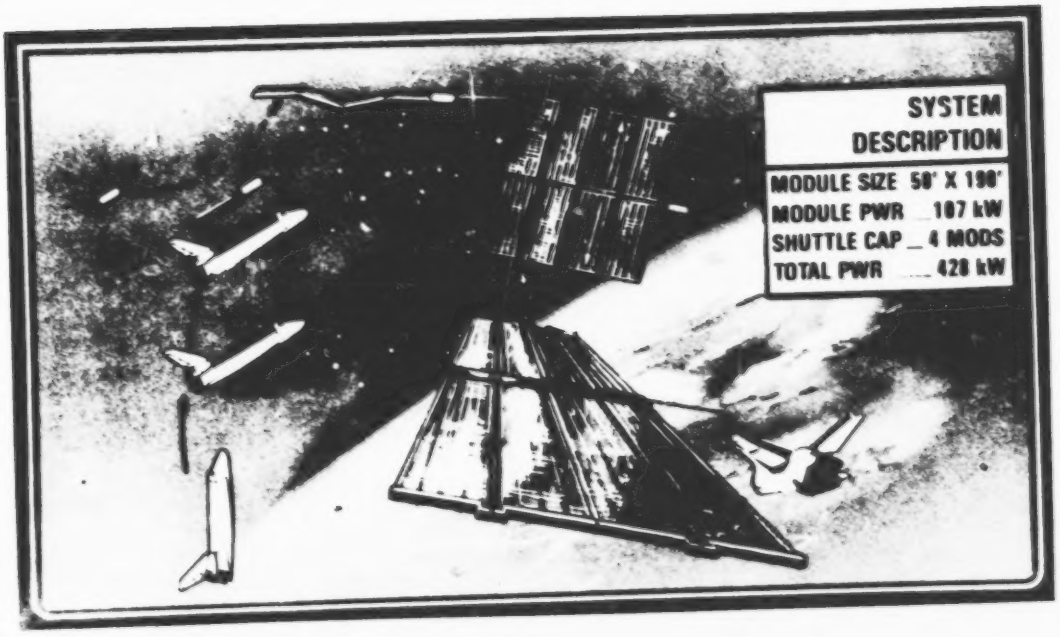
HIGH FLUX CONCENTRATOR

TRUNCATED PENTAHEDRAL CONCEPT

- GEOMETRIC CR-5
- MODULE SIZE - 50' X 250'
- MODULE PWR - 121 kW
- SHUTTLE CAPACITY - 5 MOD
- TOTAL PWR - 606 kW BOL
- SOLAR CELLS - GaAs*

*CONCEPT ALSO ALLOWS USE OF SILICON CELLS

SELF DEPLOYABLE PLANAR CONCEPT



PLANAR ARRAY

The planar array concept for multihundred kW Earth orbital applications shown in the previous artist's concept would produce 428 kW total power at beginning of life. This would be attainable using one shuttle launch and carrying four modules (module power of 107 kW and dimensions of 50 by 190 ft). It would use large silicon solar cells (6 by 6 cm).

PLANAR ARRAY

- MODULE SIZE - 50' X 190'
- MODULE PWR - 107 kW
- SHUTTLE CAPACITY - 4 MODS
- TOTAL PWR - 428 kW BOL
- SOLAR CELLS - SILICON

SUMMARY

In summary, the multihundred kW solar array program is pursuing three discrete efforts.

The thermophotovoltaic, spectrophotovoltaic, and cassegrainian approaches will be pursued because it is believed that they have a high potential payback; however, due to the fact that they have high technology risk, the funding will be at a low sustainting level.

Due to the lack of technology risk involved in planar silicon arrays, it is felt that even a potential moderate payback justifies pursuing this area; therefore, a two-year effort to investigate the cost of large/ terrestrial cells and cell blanket technology will be undertaken.

It is believed that the high flux array approach presents only a moderate technology risk and yet a high potential payback; therefore, this is planned as the multihundred kW centerline program.

The above is felt to be a balanced, flexible approach to meeting the need for high and low risk technology options and allows emphasis to be shifted as necessitated by future advancements and needs with minimum risk and dilution of effort.

SUMMARY

- THERMOPHOTOVOLTAIC; SPECTROPHOTOVOLTAIC; CASSEGRAINIAN
  - HIGH TECHNOLOGY RISK
  - HIGH POTENTIAL PAYBACK
  - PURSUED AT LOW SUSTAINING LEVEL
- PLANAR SILICON ARRAY
  - INVESTIGATE COST EFFECTIVENESS OF LARGE/TERRESTRIAL CELL
  - MODERATE PAYBACK POSSIBLE
  - TWO YEAR BLANKET TECHNOLOGY PROGRAM PLANNED
- HIGH FLUX ARRAY
  - MODERATE TECHNOLOGY RISK
  - HIGH POTENTIAL PAYBACK
  - PLANNED AS CENTERLINE PROGRAM

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THERMAL MANAGEMENT FOR HIGH POWER SPACE PLATFORM SYSTEMS

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National Aeronautics and Space Administration
Washington, D.C.

Spacecraft designed to accomplish the requirements for long term orbital applications missions planned for the late 1980's and 1990's in which large amounts of electrical energy are generated and utilized will introduce major thermal control and thermal management problems that will challenge current technology capabilities.

In the past thermal management was not an overriding factor in spacecraft design and in general the dissipation of waste heat and the control of spacecraft and instrument temperatures was considered to be a local temperature control problem. This was a reasonable approach when only small amounts of heat were required to be dissipated and which could easily be accommodated with passive techniques.

With future spacecraft power requirements expected to be in the order of 100 to 250 kilowatts and orbital lifetimes in the order of five to ten years, new approaches and concepts will be required that can efficiently and cost effectively provide the required heat rejection and temperature control capabilities.

In October 1979, OAST initiated the planning to develop the commensurate technologies necessary for the thermal management of a high power space platform representative of future requirements. The plan to be developed was to achieve technology readiness by 1987. Representatives of Goddard Space Flight Center, Marshall Space Flight Center, Johnson Space Center, Lewis Research Center, and Air Force Wright Aeronautical Laboratories actively participated in the development of the plan. The approach taken in developing the program was to view the thermal requirements of the spacecraft as a spacecraft system rather than each as an isolated thermal problem. The program resulting from these efforts are described in the attached charts.

The program plan proposes 45 technology tasks required to achieve technology readiness. Of this total, 24 tasks were subsequently identified as being pacing technology tasks and were recommended for initiation in FY 1980 and FY 1981. The balance of the tasks were proposed for initiation in FY 1982 and FY 1983.

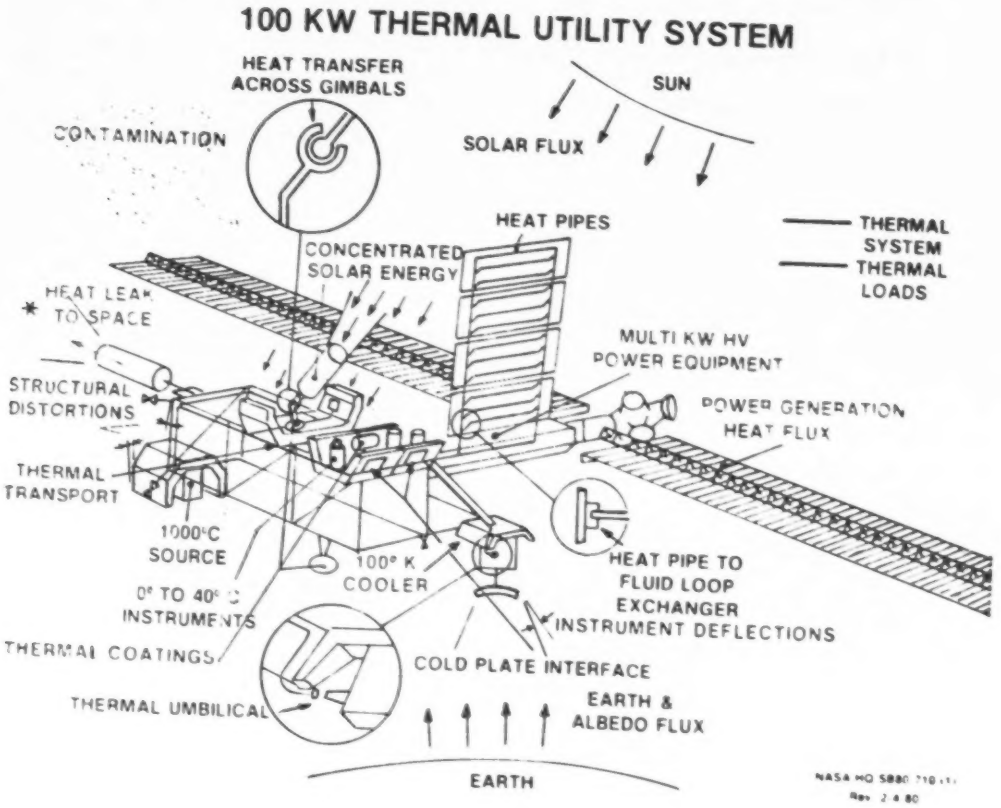
Initiation of the program is currently underway with funding of $600,000 to be provided in FY 1980. This is short of the [illegible]0,000 recommended for FY 1980, however, this does enable all the proposed tasks to be initiated. It is planned that future year funding will adhere to the recommendations of the plan.

TECHNOLOGY DEVELOPMENT REQUIREMENTS AND ISSUES

- o IMPROVED THERMAL ACQUISITION AND TRANSPORT TECHNIQUES
  - HIGH HEAT FLUX COOLING OF POWER GENERATION SYSTEMS (SUCH AS CONCENTRATORS)
    - o HIGH DENSITY COLDPLATE
    - o EQUIPMENT INTEGRAL HEAT PIPE
    - o COOLING HIGH VOLTAGE EQUIPMENT SYSTEMS
  - HEAT TRANSPORT ACROSS JOINTS
    - o FLUID OR HEAT PIPE GIMBALS
    - o HEAT PIPE/FLUID INTERFACE HEAT EXCHANGER
    - o THERMAL UMBILICAL
  - MULTIPLE SYSTEM ACQUISITION HEAT PIPE
  - THERMAL ENERGY STORAGE MATERIALS/TECHNIQUES
- o ADVANCED HEAT REJECTION CONCEPTS
  - LIGHTWEIGHT (ESP. GEOSYNC.)
  - MINIMUM LAUNCH VOLUME
  - DEPLOYABLE/CONSTRUCTABLE RADIATORS
  - MODULAR FOR GROWTH
  - HEAT PIPE ADVANCES OVER PUMPED FLUID RADIATORS
  - ACCOMMODATE SPACE ASSEMBLY/REPAIR/REPLACEMENT
  - MINIMIZE DEPLOYED AREA/HEAT PUMP
  - WIDE HEAT LOAD RANGE CAPABILITY
  - LOW DOLLARS/KW OF HEAT REJECTION

TECHNOLOGY DEVELOPMENT REQUIREMENTS AND ISSUES

- o LONG LIFE THERMAL SYSTEMS
  - MINIMUM COMPLEXITY
  - TRANSPORT SYSTEM FLUID COMPATIBILITY AND HIGH/LOW TEMP. MATERIALS
  - MICROMETECROID COUNTERMEASURES - INTEGRAL SPACECRAFT RADIATORS
  - COMPATIBILITY WITH SPACE PLASMA ENVIRONMENT AND NATURAL RADIATION
  - MAINTAINABILITY VS LONG-LIFE TRADEOFFS
- o THERMAL SYSTEMS
  - SYSTEM INTEGRATION WITH POWER GENERATION, DISTRIBUTION, AND STORAGE
  - AUTOMATIC CONTROL - MICROPROCESSOR
  - SUBSYSTEM INTERFACE/INTERACTION
  - COMPONENT/SUBSYSTEM SIMULATION AND DEMONSTRATION TESTS



THERMAL UTILITY SYSTEM FOR HIGH POWER SPACE PLATFORMS

OBJECTIVES

- o DEVELOP THE COMMENSURATE TECHNOLOGIES NECESSARY FOR THERMAL MANAGEMENT, THERMAL ACQUISITION AND TRANSPORT, AND HEAT REJECTION FOR LARGE POWER (>100KW) SPACE PLATFORM SYSTEMS
- o PROVIDE A 1987 TECHNOLOGY READINESS FOR A PLATFORM THERMAL UTILITY SYSTEM, INTEGRAL TO SPACE PLATFORM AND INSENSITIVE TO MULTIDISCIPLINARY USER LOADS
- o REDUCE COMPONENT AND SUBSYSTEM LIFE-CYCLE COSTS AND PROVIDE ECONOMICAL BASIS FOR AN EFFICIENT POWER-THERMAL SYSTEM

THERMAL UTILITY SYSTEM FOR HIGH POWER SPACE PLATFORMS

Working Group Top (#1) Priority Assessment

TASK #	TECHNOLOGY ISSUE	Center	FY 1980	FY 1981	FY 1982
	Thermal Management				
1.	Conduct system analysis of thermal management system requirements for a large capacity, high voltage utility service.	LeRC	60	75	-
5.	Analyze centralized thermal utility potential for thermal control of multi-discipline instruments with varying requirements.	GSFC	25	-	-
6.	Scope the platform thermal distortion interactions with instrument and subsystem stability requirements.	GSFC	25	LSST	-
9.	Investigate the redundancy and fail safe approaches to achieve reliability in thermal systems integration.	MSFC	-	20	50
10.	Develop efficient centralized thermal transport and temperature control scheme, i.e. collection and rejection, over wide band of heat loads.	JSC	75	100	150
12.	Improve science/application instrumentation temperature control schemes.	GSFC	75	90	125
13.	Investigate the impact on system thermal design factors imposed by military high reliability-survivability requirements, e.g., laser hardening, deployable-retractable radiators, etc.	AFWAL	-	50	50
24.	Study integration schemes for waste heat utilization prior to radiator rejection.	LeRC	-	40	-
46.	Study the conflicting relationship of incorporating an "up-front" thermal management system design with the expected step-wise growth of orbital power systems.	MSFC	-	20	50
	Thermal Acquisition & Transport				
18.	Develop and test physical heat transport system interfaces for thermal umbilical, fluid/heat pipe disconnects, gimbal joints, flex joints, contact heat exchanger, etc. components.	MSFC JSC	125	150	300
19.	Identify thermal interface concepts for instruments/support structures integration into centralized thermal transport system.	GSFC MSFC	60	80	-
20.	Explore new heat pipe designs to permit high heat transport that minimizes impact on heat transfer efficiency.	JSC	100	150	175
16.	Study contamination, surface charging and degradation effects on thermal control surfaces.	GSFC MSFC	50	80	100
29.	Develop high thermal conductivity materials for thermal joint interfaces.	LeRC	LSST	LSST	LSST

THERMAL UTILITY SYSTEM FOR HIGH POWER SPACE PLATFORMS

Working Group Top (#1) Priority Assessment

TASK #	TECHNOLOGY ISSUE	Center	FY 1980	FY 1981	FY 1982
	Thermal Acquisition & Transport (Continued)				
32.	Analyze and define thermal buss concepts.	JSC	50	90	160
53.	Explore application of heat pipes and solid thermal conductors integral to instrumentation and power equipment.	LeRC GSFC MSFC	60	100	-
	Heat Rejection				
37.	Demonstrate heat rejection limits to extend length heat pipe concepts.	JSC MSFC	50	100	175
38.	Survey and select competing heat pipe design concepts for breadboard development, e.g., osmetic, etc.	GSFC	50	100	100
39.	Conduct parametric scaling optimization analyses for high power heat pipe rejection concepts.	JSC	25	-	-
40.	Demonstrate the heat pipe radiator interface performance with thermal transport schemes.	JSC	-	50	100
	Life Cycle Costs				
42.	Analyze the "long-life" requirement in thermal components and subsystems against replacement, modular assembly and maintainability tradeoffs.	MSFC JSC LeRC GSFC	20	20	75
44.	Prioritize low-cost driver technologies in thermal control.	JSC GSFC LeRC MSFC	10	30	50
		Total	860	1345	1610

THERMAL UTILITY SYSTEM FOR HIGH POWER SPACE PLATFORMS

Working Group High (#2) Priority Assessment

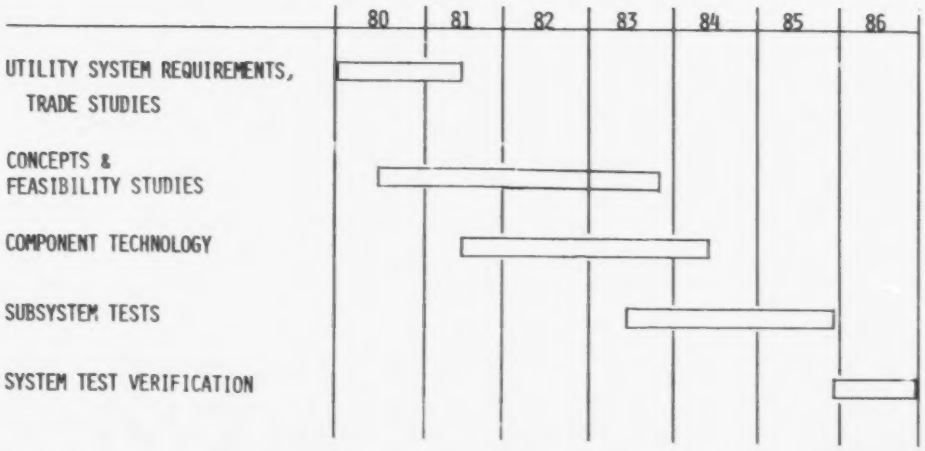
TASK #	TECHNOLOGY ISSUE	Center	FY 1982	FY 1983	FY 1984	FY 1985
	Thermal Management					
2.	Define a representative thermal load utility profile for a broad range of user and operational requirements.	LeRC	50	25	-	-
4.	Define the interaction of the spacecraft charge environment with thermal control contamination.	GSFC LeRC AFWAL	40	60	90	40
11.	Investigate induced contamination environment effects on power-thermal surfaces.	GSFC	50	50	50	50
51.	Investigate the timing extent of prototype and large ground test verification at the system and subsystem level.	MSFC JSC	100	100	75	75
47.	Conduct modeling and analysis of thermal system performance and operating characterization.	LeRC JSC	80	100	100	200
	Thermal Acquisition and Transport					
15.	Investigate thermal system sensitivity parameters to instrument and subsystem changeouts.	GSFC JSC	50	75	100	-
48.	Investigate thermal system interfaces (e.g. cold plates) with highly concentrated thermal loads from high watt density devices and HV power modules.	GSFC MSFC AFWAL	100	100	100	-
17.	Investigate alternative fluids utilization and identify tradeoff options.	LeRC GSFC	100	150	100	50
22.	Study the thermal control tradeoffs of inductive power transfer versus HVDC.	LeRC	50	-	-	-
23.	Investigate large scale thermal storage devices for heat load leveling and large thermal transients.	LeRC MSFC AFWAL	150	100	100	50
27.	Explore polymeric and flexible heat pipe utilization in thermal connectors.	LeRC	100	-	100	-
30.	Evaluate system capabilities of a representative thermal transport concept employing fluid loops, heat pipes and controlled heat conduction umbilical.	LeRC JSC	300	300	300	200
	Heat Rejection					
33.	Explore centralized and decentralized systems of heat rejection, e.g., heat pipe radiators integral to spacecraft hull and deployable/retractable radiators.	JSC AFWAL	80	80	80	-
49.	Define the potential and application of advanced heat pipes, e.g. osmotic, ion-drag, etc.	GSFC LeRC	100	100	100	100
	Total, $K	XX	1350	1340	1295	765

THERMAL UTILITY SYSTEM FOR HIGH POWER SPACE PLATFORMS

Working Group Deferred Start (#3) Priority Assessment

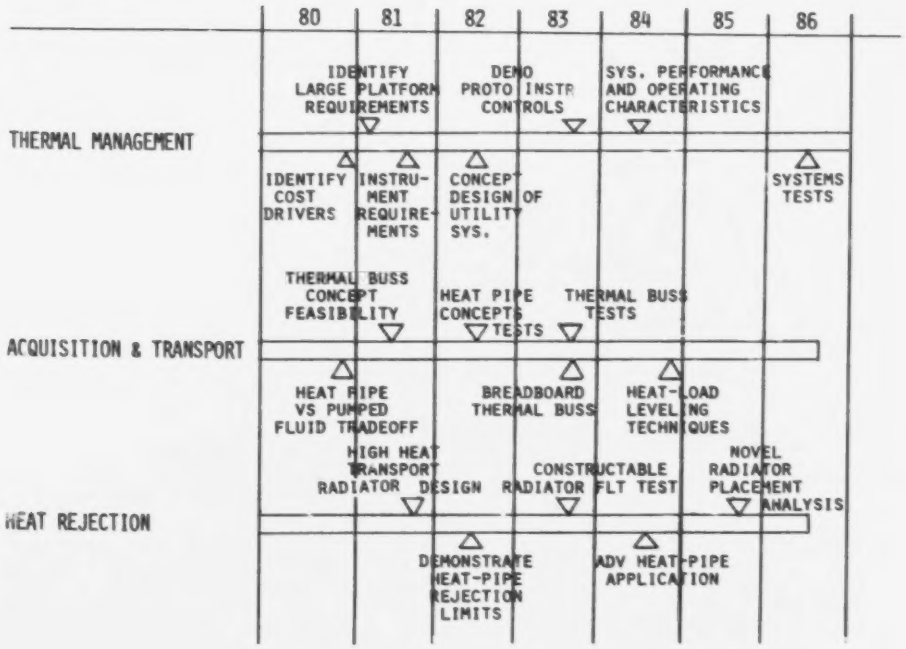
TASK # TECHNOLOGY ISSUE	Center	FY 1983	FY 1984	FY 1985	FY 1986
Thermal Management					
3. Study the integration of thermal control electronics, e.g. sensors and micro-processors with power processing electronics.	MSFC LeRC GSFC	150	100	200	200
8. Do life support system requirements impose unique thermal management constraints?	JSC	50	50	-	-
14. Develop thermal radiation environment and thermal analyzer analytical tools for design and verification of large power-thermal systems.	JSC	180	300	300	100
Thermal Acquisition and Transport					
26. Explore techniques for structure heat path utilization, e.g. controlled heat leaks to outer spacecraft hull.	LaRC GSFC MSFC	150	100	50	50
Heat Rejection					
34. Analyze thermal radiation environments in novel radiator placement locations.	JSC	75	100	100	-
35. Study heat rejection integration with higher efficiency regenerative fuel cell-electrolysis energy storage systems.	JSC LeRC	100	100	-	-
36. Analyze special purpose power reserves where exotic battery concepts, e.g. Na and Li, may introduce significant thermal control gradients compared to NiH_2 approaches.	MSFC JSC LeRC	125	100	75	-
41. Study GaAs concentrator or other high temperature array concepts (e.g. thermal-voltaic and spectrophotovoltaic convertors) require different approaches in heat dissipation.	MSFC	200	200	100	100
TOTAL, $K	XX	1080	1050	825	450

THERMAL MANAGEMENT



THERMAL MANAGEMENT

(MILESTONE SCHEDULES)



THERMAL UTILITY SYSTEM FOR HIGH POWER SPACE PLATFORMS

RESOURCE 1987 TECHNOLOGY READINESS SCHEDULE, $K (FY '80$)

	# TASK	FY '79	FY '80	FY '81	FY '82	FY '83	FY '84	FY '85	FY '86	TOTALS
THERMAL MANAGEMENT										4297
Priority #1	11	47	290	445	550					
Priority #2	5				120	335	315	365		
Priority #3	3					380	450	500	300	
THERMAL ACQUISITION & TRANSPORT										5030
Priority #1	7	75	445	650	735					
Priority #2	7				850	825	800	300		
Priority #3	1					150	100	50	50	
HEAT REJECTION										2815
Priority #1	4		125	250	375					
Priority #2	2				180	180	180	100		
Priority #3	4					550	500	275	100	
TOTAL		122	860	1345	3010	2420	2345	1590	450	12142

THERMAL MANAGEMENT
(MAJOR CENTER EFFORTS)

JSC

- DEVELOP THERMAL TRANSPORT AND TEMPERATURE CONTROL SCHEMES
- THERMAL BUSS
- HEAT REJECTION CONCEPTS ANALYSIS
- RADIATORS CONCEPTS; DEPLOYABLE, CONSTRUCTABLE

LERC

- THERMAL SYSTEM REQUIREMENTS FOR LARGE PLATFORMS
- THERMAL CONTROL TRADEOFFS
- WASTE HEAT UTILIZATION
- HIGH THERMAL CONDUCTIVITY MATERIALS

GSFC

- COOLING AND CONTROL OF MULTI-DISCIPLINE INSTRUMENTS
- THERMAL INTERFACE CONCEPTS FOR INSTRUMENTS
- HEAT-PIPE DESIGN CONCEPTS

MSFC

- THERMAL CONTROL SURFACES
- THERMAL SYSTEMS INTEGRATION
- TRANSPORT SYSTEM INTERFACES

FY 1980 THERMAL MANAGEMENT PROGRAM

JSC: 300K

- o HEAT PIPE FEASIBILITY DEMONSTRATION
- o BEGIN RADIATOR SYSTEM DESIGN
- o IDENTIFICATION OF THERMAL BUSS REQUIREMENTS & CONCEPT DEFINITION
- o IDENTIFICATION OF INTERFACE REQUIREMENTS

MSFC: 60K

- o THERMAL CONTROL COATINGS

LERC: 120K

- o CONTINUE VOUGHT STUDY (UNMANNED MODULE PROBLEMS, INTEGRATION PROBLEMS WITH THERMAL BUSS CONCEPT)
- o PRELIMINARY EFFORTS FOR MEASUREMENT OF HIGH PERFORMANCE SOLID THERMAL CONDUCTORS

GSFC: 120K

- o IDENTIFY INSTRUMENT THERMAL CONTROL REQUIREMENTS & INSTRUMENT TECHNOLOGIES
- o SELECTION OF HEAT TRANSFER DEVICES FOR BREADBOARD DEVELOPMENT

THERMAL MANAGEMENT SYSTEM
BENEFITS

- o IMPROVE BASIS FOR SCALE-UP TO VERY LARGE POWER SYSTEMS
- o PROVIDE COMMENSURATE DATA BASE IN THERMAL UTILITY DESIGN OPTIONS FOR LARGE CAPACITY, HIGH VOLTAGE POWER GENERATION AND STORAGE CAPABILITIES
- o REDUCED RISK BY EXPANDING EXPERIENCE/DATA BASE IN LONG-LIFE AND HIGH TEMPERATURE COMPONENTS AND MINIMIZING SYSTEM DESIGN COMPLEXITY
- o REDUCED DEVELOPMENT COSTS THROUGH MODULARITY, SYSTEMS LEVEL DESIGN APPROACH, INTEGRATION WITH OTHER SUBSYSTEMS, REDUCED WEIGHT AND VOLUME
- o IMPROVED UTILIZATION OF ORBITER AND SHUTTLE CAPABILITIES
- o EXTENDED LIFETIME THROUGH MAINTAINABILITY/REPLACEABILITY, MATERIALS COMPATIBILITY, AND REDUCED ADVERSE ENVIRONMENTAL INTERACTIONS
- o REDUCED OPERATIONAL AND PAYLOAD INTEGRATION COSTS WITH CENTRALIZED POWER-THERMAL SYSTEM
- o REDUCED COSTS FOR ALL USERS THROUGH INSTRUMENT THERMAL DESIGN IMPROVEMENTS AND CENTRALIZED THERMAL UTILITY

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ELECTROCHEMICAL ORBITAL ENERGY STORAGE (ECOES) TECHNOLOGY PROGRAM

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Since the earliest days of manned space flight utilizing fuel cell power systems, the potential for increased mission duration, which may be made possible by recycling reactants, has been a strong attraction to advanced mission planners and technologists. Studies have been conducted since the mid-60's geared toward assessing this potential in light of the missions in vogue at the time. This concept is generally referred to as a Regenerative Fuel Cell System. The concept will now be reviewed by describing salient features, study history, study results, technology base, and an overview of the on-going technology program. Finally, several illustrations will be given depicting the versatility and flexibility of a Regenerative Fuel Cell Power and Energy Storage System.

The principal elements of a Regenerative Fuel Cell System combine the fuel cell and electrolysis cell with a photovoltaic solar cell array, along with fluid storage and transfer equipment. The power output of the array (for LEO) must be roughly triple the load requirements of the vehicle since the electrolyzers must receive about double the fuel cell output power in order to regenerate the reactants (2/3 of the array power) while 1/3 of the array power supplies the vehicle base load. The working fluids are essentially recycled indefinitely. Any resupply requirements necessitated by leakage or inefficient reclamation is water - an ideal material to handle and transport. Any variation in energy storage capacity impacts only the fluid storage portion, and the system is insensitive to use of reserve reactant capacity.

CONCEPT FEATURES - REGENERATIVE FUEL CELL SYSTEM

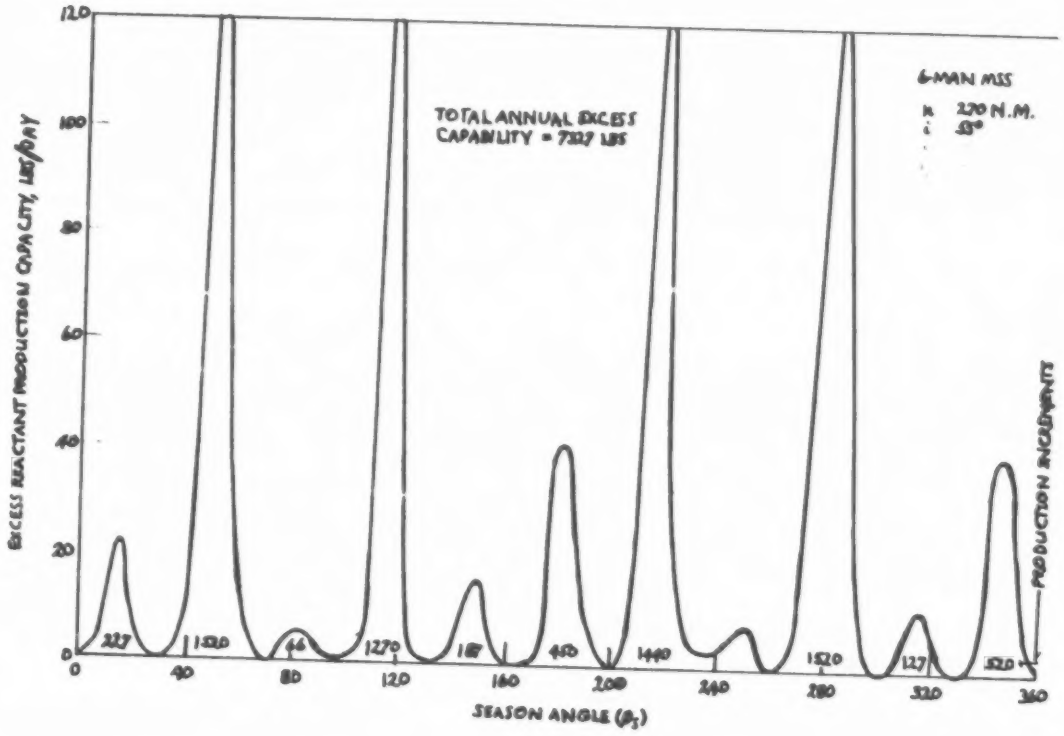
- MATES H_2/O_2 FUEL CELLS AND ELECTROLYSIS CELLS WITH PHOTOVOLTAIC SOLAR CELL ARRAYS.
- RECYCLES WORKING FLUIDS ($H_2O/H_2/O_2$) INDEFINITELY.
- RESUPPLY REQUIREMENTS - WATER.
- ENERGY STORAGE CAPACITY VARIATIONS - FLUID TANKS.
- DEEP DISCHARGE INSENSITIVITY - USE OF RESERVE CAPACITY.

In addition to several analyses conducted within the Agency, four specific studies were contracted for. The first was conducted by NAR as an add-on task for the Modular Space Station Study to compare the concept with a NiCd battery system for a 6-man, 25 kW vehicle. Lockheed and Life Systems then performed detailed design analyses of the approach and produced Design Data Handbooks. The most recent effort was a McDonnel-Douglas Space Construction Base Study requiring a 100 kW_e power system.

HISTORY - RFC SYSTEM STUDIES

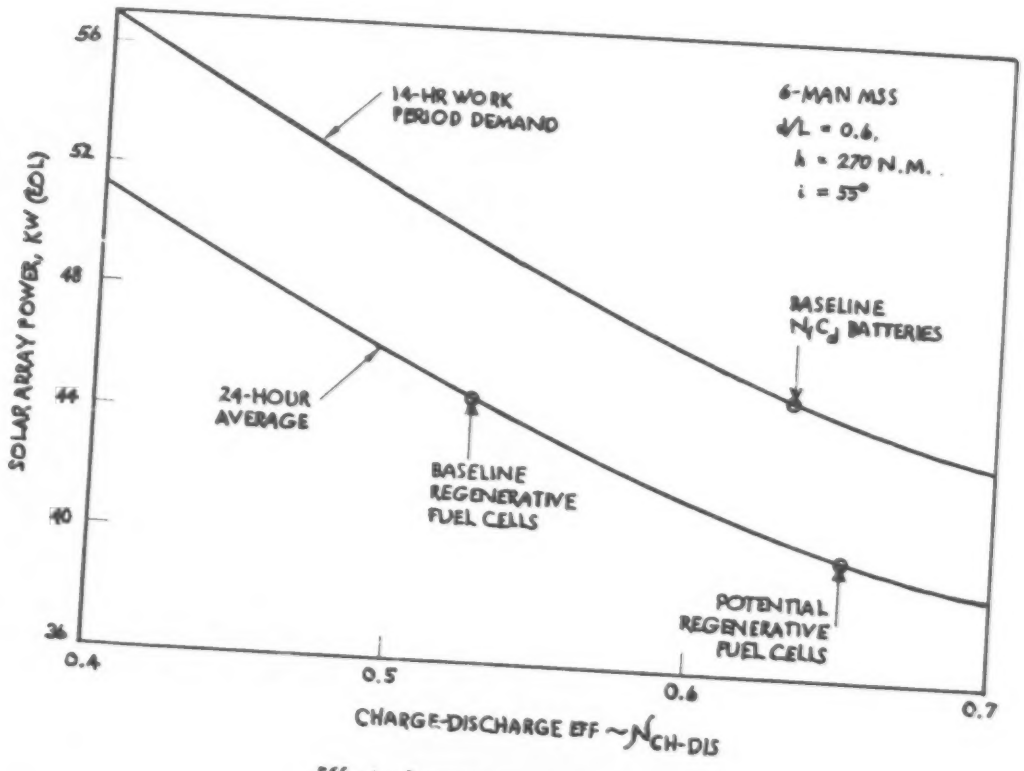
- NAR - 1972, MODULAR SPACE STATION, PHASE B EXTENSION
  6-MAN, 25 KW, 10 YEAR LIFE
- LMSD - 1972, DETAILED SYSTEM DESIGN DATA HANDBOOK
- LSI -1972, DETAILED SYSTEM DESIGN DATA HANDBOOK
- MDAC - 1977, SPACE CONSTRUCTION BASE SYSTEMS ANALYSIS
  100 KW, 10 YEAR LIFE

The analysis was performed in the Rockwell study as to how the seasonal solar angle may relate to the RFC System. This is plotted in terms of excess reactant production capability. It is shown that the total annual excess rate is 7,327 pounds for the basic 25 kW (net) system. Thus by sizing storage tank capacity to store the excess, the array size can be proportionately reduced.



EPS Excess Reactant Production Versus Season Angle

The 24-hour day was divided into a 14-hour work (high activity) period and a 10-hour sleep (low activity) period. By optimizing the reactant storage capacity and sizing the array for a 24-hour average day, it is seen that at a fixed charge-discharge efficiency, the array power (size) may be reduced by about 10%.



Effect of Energy Storage on Solar Array Size

The effect of this is shown for the RFC vs. the NiCd battery system. Case 1 is for the 14/10 hour work/sleep design, and case 2 is is for the 24-hour average. The RFC weight adjusts downward slightly, while the battery system, because of the linear relationship of weight vs. capacity, must increase by approximately 2700 pounds.

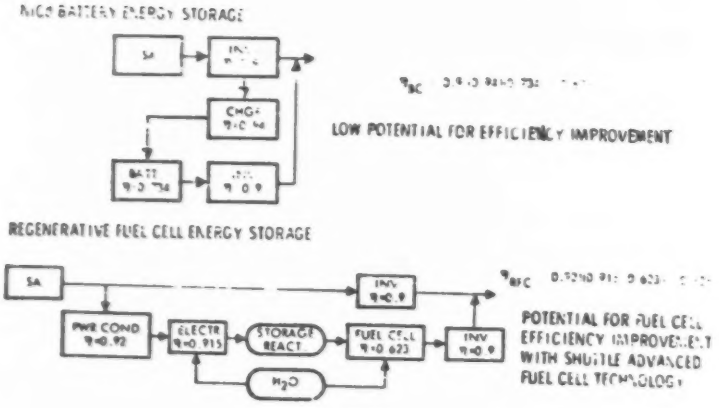


Figure 6-40. EPS Energy Storage Efficiency Analyses

Table 6-19. Solar Array Area Comparison

SOLAR ARRAY AREA SENSITIVE TO
- ENERGY STORAGE CONCEPT EFFICIENCY
- ENERGY STORAGE CAPACITY

ENERGY STORAGE CONCEPT	NiCd BATTERIES	REGENERATIVE FUEL CELLS
CHARGE/DISCH EFFICIENCY	0.625	0.525
CASE 1		
SOLAR ARRAY SIZED TO 14 HR WORK DAY		
LOAD + ENERGY STORAGE	31.21 KW	31.21 KW
TOTAL EPS LOSSES	13.66	17.79
SOLAR ARRAY POWER *	44.87	49.00
SOLAR ARRAY AREA, FT²	1,780	0,500
ENERGY STORAGE WEIGHT LB	9,157	6,350
EPS SUBSYSTEM WEIGHT LB	22,932 ←	16,815
CASE 2		
SOLAR ARRAY SIZED TO 24 HOUR AVERAGE		
LOAD + ENERGY STORAGE	27.05 KW	27.05 KW
TOTAL EPS LOSSES	11.75	16.62
SOLAR ARRAY POWER *	38.8	43.67
SOLAR ARRAY AREA (FT²)	1,980	1,540
ENERGY STORAGE WEIGHT (LB)	13,613	9,813
EPS SUBSYSTEM WEIGHT, (LB)	25,020	18,351 ←

*END OF LIFE POWER 30% DEGRADATION ASSUMED

DECREASED SOLAR ARRAY AREA FOR REGENERATIVE FUEL CELL ENERGY STORAGE

The MDAC Study results compare the four energy storage systems studied. The RFC ranges from 25% lighter to less than 1/2 the weight of competitors. Ten year resupply weight is even more pronounced as is energy density. And, as alluded to earlier, deep discharge (depleting the reactant supply) has no adverse effect upon the Regenerative Fuel Cell System.

ENERGY STORAGE CHARACTERISTICS SUMMARY*

	NiCd	ADVANCED NiCd	NiH_2	REGENERATIVE FUEL CELLS
ARRAY OUTPUT, BOL, KWe				
• TYPICAL	214.7	209.0	217.1	230.7
• SOLAR ORIENTED	233.4	227.2	236.0	250.8
ARRAY AREA, M^2	2,407	2,343	2,434	2,587
STORAGE EFFICIENCY, %	62	65.7	60.8	54.1
DEPTH OF DISCHARGE, %	14.5	14.5	18.6	33
ENERGY DENSITY(2), W-H/KG	3.93/27.08	6.39/44.1	9.49/51	25.0/75.1 ←
EXPECTED LIFE, YEAR				
• DEMONSTRATED	3.33	NONE	~1	5+/3+(1)
• DESIGN	3.33	3.33	3.33	5
• POTENTIAL	5	5	10	10
PEAK LOAD CAPABILITY	~10X	~10X	2-10X	~4X
LOAD AVERAGING POTENTIAL	FAIR	FAIR	FAIR	GOOD
LAUNCH WEIGHT, KG	34,763	25,868	21,450	16,083 ←
RESUPPLY WEIGHT (10 YR), KG	41,919	25,746	17,356	2,994 ←

*100 KWe AVERAGE AT INVERTER OUTPUT; FAB AND ASSEMBLY POWER PLATFORM
(1) FUEL CELL/ELECTROLYSIS CELL
(2) BATTERY: USEABLE/ABSOLUTE

A weight summary of a study conducted by JSC in 1979 is shown for a 35, 100, and 250 kW system. Capacity was sized for a 2-hour period. Thus, for a 100 kW system, the 10-year weight to orbit, 200,000 WH, yields an energy density of 15.5 WH/lb. For direct comparison with a battery system, it may be necessary to subtract out those elements not normally included in the energy density figure.

H_2-O_2 (DEDICATED UNITS) WEIGHTS, kg

ITEM	POWER LEVEL-kW		
	35	100	250
Fuel Cell Unit (FCU)	196	487	1,118
Electolysis Unit (EU)	522	949	2,373
Hydrogen Tank	51	111	280
Oxygen Tank	31	63	137
Water Tank, Low Press.	2	4	7
Water Tank, High Press.	2	4	7
Power Supply to EU	90	257	643
Regulator	80	230	574
Piping	23	34	57
Pipe Fittings and Valves	23	34	57
Pump, Water Circ. and Press.	9	18	34
Structure*	97	211	524
Reactant	8	22	55
Incremental Solar Array**	348	995	2,484
Incremental Radiator	180	515	1,287
Total Weight	1,662	3,934	9,737
Ten-Year Weight to Orbit; 5-Year Life	2,559	5,857	14,579

*Structure weight assumed as 10% of combined weights of FCU, EU, tanks, power supply and regulator.

**Increment of array above that for equivalent battery system.

The technology base for the Regenerative Fuel Cell dates from 1962 with the solid polymer electrolyte fuel cell for the Gemini Program. The Apollo Program provided for a different technology - the Bacon-type cell - in parallel with the SPE. Several technology programs are listed which led up to the present Shuttle fuel cell - the alkaline capillary matrix type.

TECHNOLOGY BASE - FUEL CELLS

- GEMINI - SOLID POLYMER ELECTROLYTE (ACIDIC SPE)
  - 1962 - 1966
  - 1 KW MODULES
  - 400 HOURS LIFE (> 1000)
  - 75 - 125°F
  - 30 PSI
- APOLLO/SKYLAB - BACON-TYPE (ALKALINE KOH)
  - 1962 - 1974
  - 1.4 KW MODULES
  - 400 HOURS LIFE (>1000)
  - 385 - 430°F
  - 60 PSI
- TECHNOLOGY (APOLLO-X, AAP) - ALKALINE CAPILLARY MATRIX
  - 1964 - 1970
  - 2 KW MODULES
  - 2500 HOURS DEV. TEST LIFE
  - 180°F
  - 45 PSI
- TECHNOLOGY (PRE-SHUTTLE) PROGRAMS

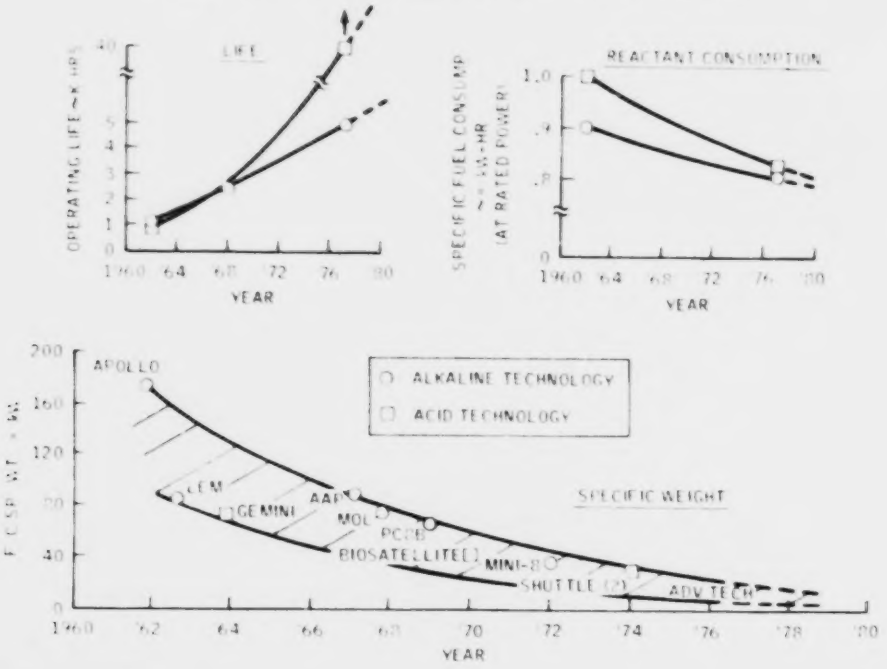
CAPILLARY MATRIX (KOH)	SPE (ACIDIC)
1970 - 1974	1970 - 1979
5 KW MODULE	2.5 KW STACK
5000 HOURS	5000 HOURS
180°F	180°F
60 PSI	60 PSI

- VARIOUS ELECTROLYSIS PROGRAMS FOR LIFE SUPPORT AND H_2 PRODUCTION.
- TUG FUEL CELL DEVELOPMENT CAPILLARY MATRIX.
- "LIGHTWEIGHT" FUEL CELL TECHNOLOGY.
- MATRIX, ELECTRODE/CATALYST, MATERIALS TECHNOLOGY.

Substantial weight reduction has been realized. The Apollo fuel cell weighed in at about 185 pounds/kW. The Shuttle fuel cell weighs about 30 pounds. Advanced technology indicated a weight of less than 20 pounds kW.

Operating lifetimes also show a marked increase. The Gemini and Apollo fuel cells were required to operate approximately 400 hours and under certain conditions could go to 1000 hours. Shuttle development hardware has operated in excess of 5000 hours, and advanced technology test hardware is operating in excess of 40,000 hours.

FUEL CELL TECHNOLOGY EVOLUTION



The program now in progress has been in planning since 1977. It is oriented toward producing technology capable of providing large incremental increases in orbital power availability from about 35 kW (the approximate Shuttle limit) to about 500 kW

OVERVIEW OF PROGRAM

- OBJECTIVE: TO MAKE READY A H_2/O_2 ELECTROCHEMICAL CELL TECHNOLOGY BY 1985-86 TIME PERIOD SUITABLE FOR SELECTION FOR LARGE (100-500 KW), LONG-TERM (5-10 YEARS) ORBITAL ENERGY STORAGE REQUIREMENTS.

- APPROACH: TO BE ACCOMPLISHED OVER A PERIOD OF APPROXIMATELY 7 YEARS THROUGH A SERIES OF CONTRACTED EFFORTS AND SUPPORTED BY THE AGENCY THROUGH ANALYSES, FIELD BREADBOARD FEASIBILITY TESTING, AND INTEGRATED TESTING OF ENGINEERING MODELS TO DEMONSTRATE TECHNOLOGY READINESS.

The schedule for the 7-year program is shown with major milestones. The reversible type cell is not showing and appreciable advantage over the dedicated cell approach, and that task will be terminated in a few months when present testing is completed. Cell commonality is being phased into other appropriate tasks with the next contract increment. The State-of-the-Art analysis was completed, but will be updated as the program moves ahead.

PROGRAM GOALS

- STATE OF THE ART ANALYSIS
  - INITIAL REPORT - 11/79
  - ANNUAL UPDATE REFLECTING TECHNOLOGY IMPROVEMENTS
- BREADBOARD FEASIBILITY TESTING
  - CONTRACTOR CHECKOUT AND DELIVERY - 5/82
  - FIELD TESTING - 5/82 - 12/82
  - ACIDIC/ALKALINE SELECTION - 5/83
- ENGINEERING MODEL HARDWARE TESTING
  - CONTRACTOR CHECKOUT AND DELIVERY - 10/85
  - "TECHNOLOGY READINESS" DEMONSTRATION - 10/85 - 5/86

1980 PROGRAM STATUS

JSC

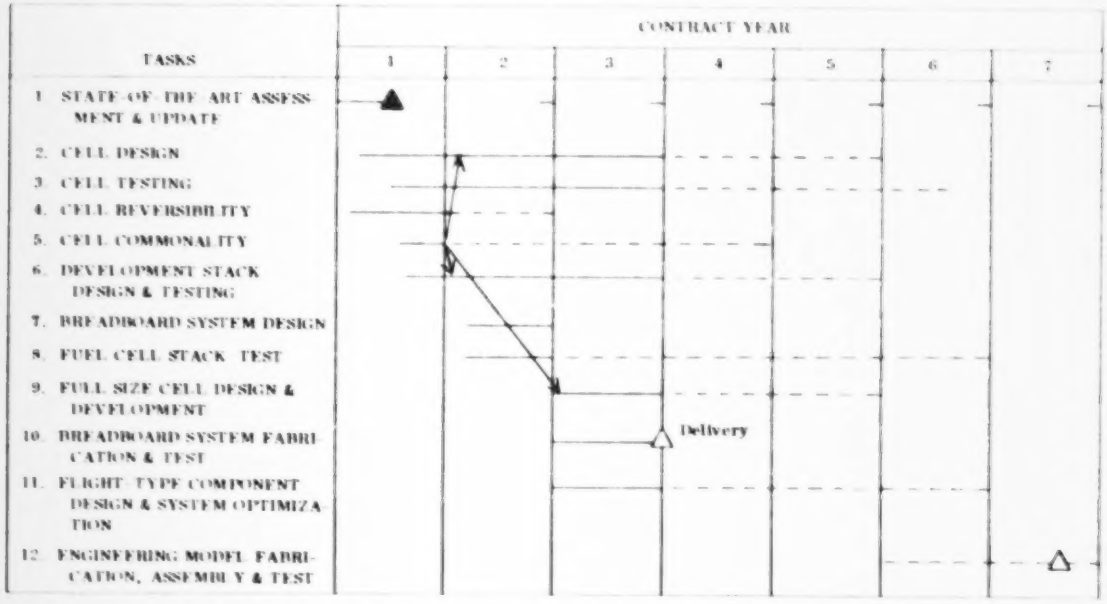
- CONTRACT - 5/1/79 - G.E. SPE TECHNOLOGY
  - SOA ANALYSIS
  - CELL AND MATERIALS DEVELOPMENT
  - ADVANCED DESIGN CONCEPTS

LeRC

- CONTRACT - 8/1/79 - LSI ALKALINE O_2 ELECTRODES
  - 2 - "SUPER" } (CELL TESTS)
  - 2 - "ADVANCED" }
- CONTRACT - 8/31/79 - UTC ALKALINE CAPILLARY MATRIX
  - LONG-DURATION, LO TEMP. CELL TEST
  - 3 KW TUG STACK TEST
  - ADVANCED ORBITER-TYPE ELECTRODE TEST

PROCUREMENT ACTION FOR CONTRACT RENEWAL IN PROGRESS.

ELECTROCHEMICAL CELL TECHNOLOGY
DEVELOPMENT FOR ORBITAL ENERGY STORAGE



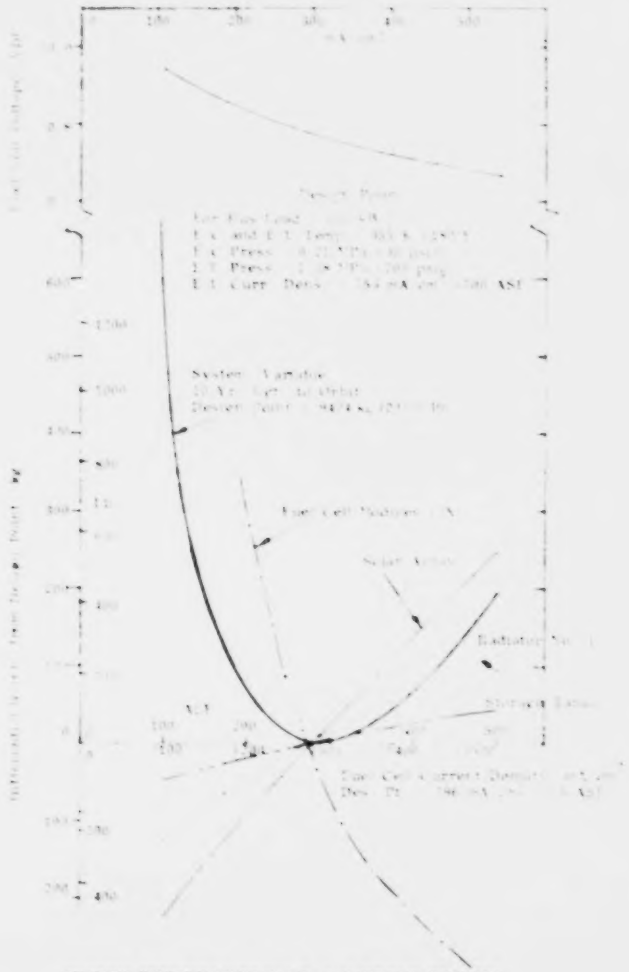
An example of the SOA analysis is shown. This is a computer optimization of the various parameters affecting the overall weight. Total system energy density based upon 200,000 WH of stored energy is 9.62 WH/lb. Subtracting out the solar array weight yields an energy density figure of 24 WH/lb, 10-year weight to orbit.

ECOD-1 1144 10/26/79 CASE 330 DESIGN POINT

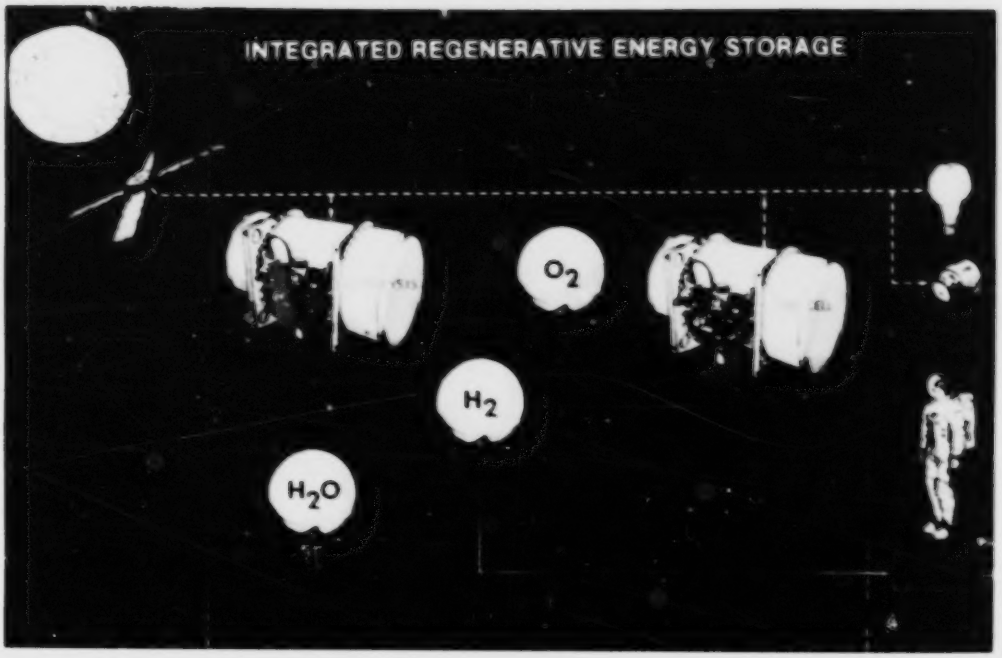
DEDICATED ELECTROLYSIS/FUEL CELL SUMMARY

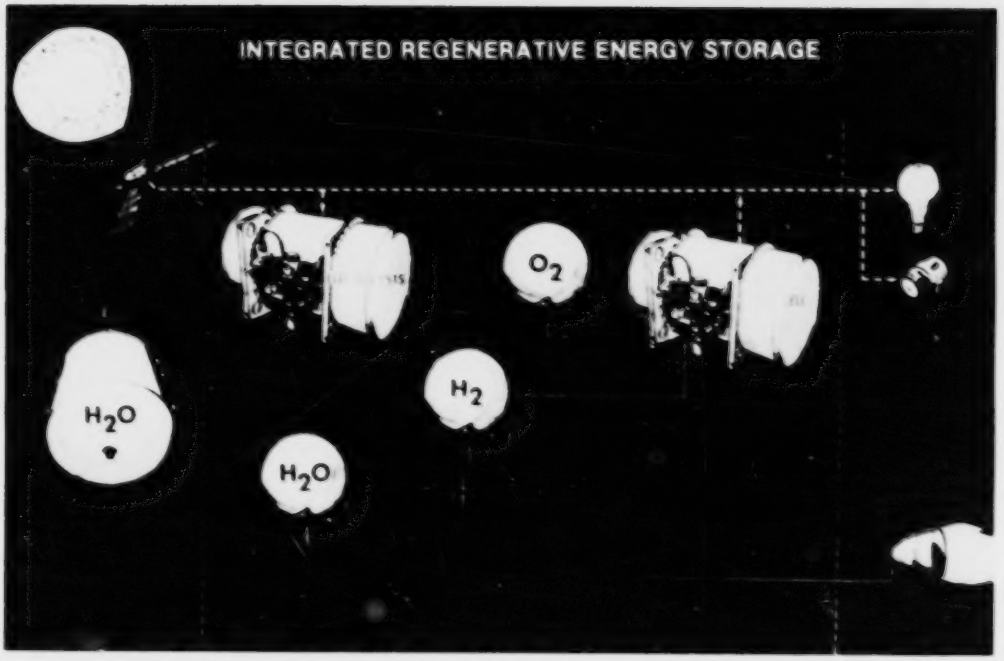
BUS POWER	100.0	KW
BUS VOLTAGE	105.0	VOLTS
FUEL CELL OPERATING CONDITIONS		
MEAN CELL PRESSURE	30.0	PSIA
MEAN CELL TEMPERATURE	180.0	DEG F
CELL CURRENT DENSITY	275.0	AMP/SQ FT
CELL VOLTAGE	.7896	VOLTS
NO. OF CELLS PER MODULE	137.0	
NUMBER OF MODULES	4.0	
INDIVIDUAL CELL AREA	.88	SQ FT
TOTAL AREA OF CELLS	484.78	SQ FT
MODULE SPECIFIC WEIGHT	1.73	LB/SQFT
CELL CURRENT,PARALLEL MODULES	243.27	AMP
MODULES OUTPUT POWER	105.263	KW
CELL CURRENT EFFICIENCY	.9921	
PERMEABILITY LOSS(EQUIV)	2.182	AMP/SQ FT
MODULES HEAT GEN. RATE(DARK)	92.480	KW
MODULES HEAT GEN. RATE(LIGHT)	1.842	KW
ELECTROLYSIS UNIT OPERATING CONDITIONS		
MEAN CELL PRESSURE	200.0	PSIA
MEAN CELL TEMPERATURE	180.0	DEG F
CELL CURRENT DENSITY	700.0	AMP/SQ FT
CELL VOLTAGE	1.7705	VOLTS
NO. OF CELLS PER MODULE	50.0	
NUMBER OF MODULES	5.0	
INDIVIDUAL CELL AREA	.45	SQ FT
TOTAL AREA OF CELLS	132.01	SQ FT
MODULE SPECIFIC WEIGHT	3.34	LB/SQFT
CELL CURRENT, PARALLEL MODULES	313.24	AMP
MODULES INPUT POWER(LIGHT)	171.781	KW
POWER CONDITIONER INPUT POWER	182.746	KW
STANDBY INPUT POWER(DARK)	.0002	KW
STANDBY INPUT CURRENT(DARK)	.0006	AMP
CELL CURRENT EFFICIENCY	.9842	
PERMEABILITY LOSS(EQUIV)	11.051	AMP/SQ FT
MODULES HEAT GEN. RATE(LIGHT)	29.763	KW
MODULES HEAT GEN. RATE(DARK)	.251	KW
SYSTEM OPERATING CONDITIONS		
SOLAR ARRAY OUTPUT POWER	288.000	KW
IDEAL REGEN FUEL CELL EFF.	.4355	
SYSTEM ENERGY STORAGE EFF.	.3648	
WATER PRODUCED (2 HR)	199.134	LB
MINIMUM BOTTLE PRESSURE (2 HR)	40.000	PSIA
H2 STORAGE BOTTLE VOLUME	415.866	CU FT
H2 BOTTLE DIAMETER	111.40	IN.
WEIGHT SUMMARY		
SOLAR ARRAY WEIGHT	13018.73	LB
RADIATOR NO 1 WEIGHT	1788.49	LB
RADIATOR NO 2 WEIGHT	70.00	LB
H2,O2,&H2O BOTTLE WGTS	1346.62	LB
PRIMARY HEAT EXCHANGER WGT	118.33	LB
REGENERATIVE HEAT EXCH. WGT	32.32	LB
CONDENSER WEIGHT	15.34	LB
PRODUCT H2O HEAT EXCH. WGT	2.90	LB
FUEL CELL MODULES WEIGHT	837.22	LB
ELECTROLYSIS MODULES WEIGHT	440.86	LB
POWER CONDITIONER WEIGHT	913.73	LB
SYSTEM VARIABLE LAUNCH WEIGHT	18584.63	LB
SYSTEM VARIABLE 10-YR ORB. WGT	20776.44	LB

An illustration of how the various elements of a system are impacted by varying one parameter is shown. In this case the fuel cell current density design point was 275 ASF. For example, if current density is reduced the solar array area (and weight) is reduced. However, total system weight is increased. Other elements are affected also which can be traced similarly.



SYSTEM WEIGHTS VERSUS F C CURRENT DENSITY
COMPUTER CASES 142, 143, 130, 144, 145





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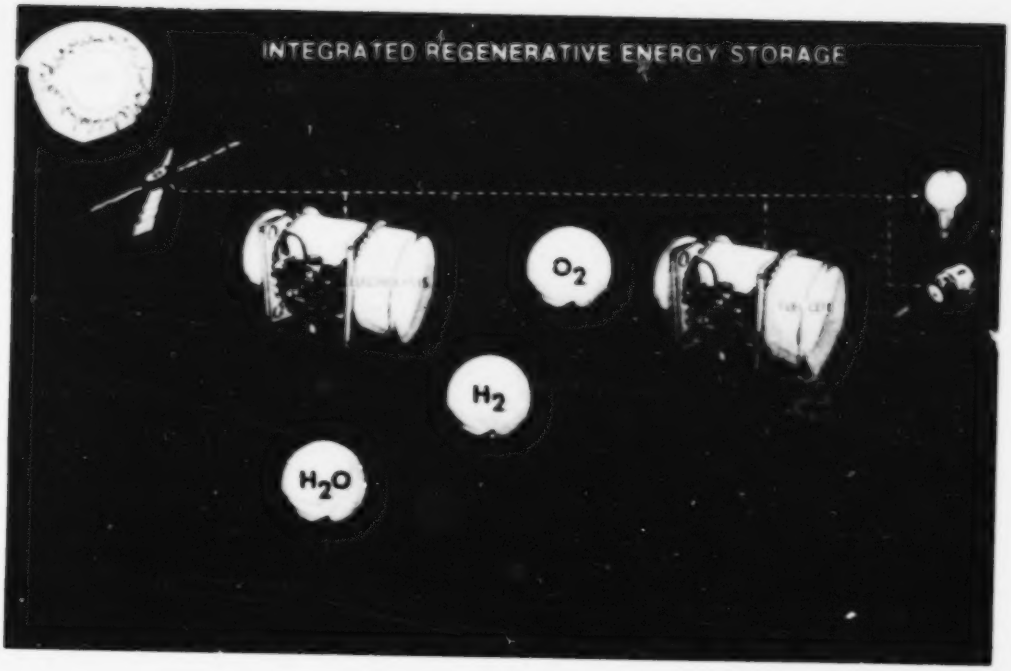

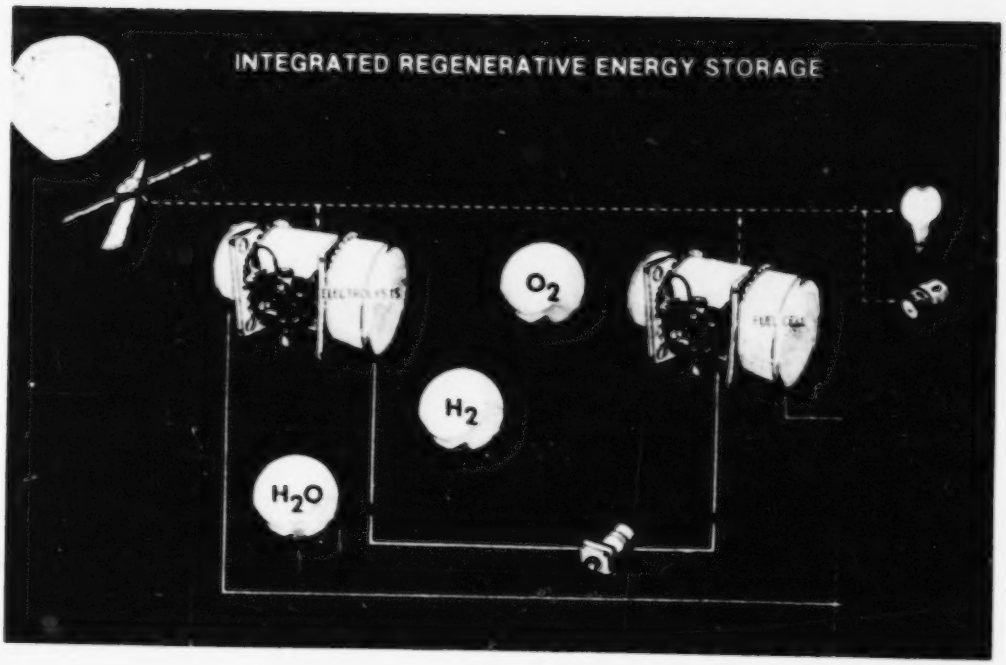

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STATUS OF NICKEL-HYDROGEN CELL TECHNOLOGY

Don R. Warnock
Aero Propulsion Laboratory

Nickel-hydrogen cell technology has been developed which solves the problems of thermal management, oxygen management, electrolyte management, and electrical and mechanical design peculiar to this new type of battery. This technology has been weight optimized for low orbit operation using computer modeling programs but is near optimum for other orbits. Cells ranging in capacity up to about 70 ampere-hours can be made from components of a single standard size and are available from two manufacturers. The knowledge gained is now being applied to the development of two extensions to the basic design: (1) a second set of larger standard components that will cover the capacity range up to 150 ampere-hours, and (2) the development of multicell common pressure vessel modules to reduce volume, cost and weight. A manufacturing technology program is planned to optimize the producibility of the cell design and reduce cost. Collectively these programs bring nickel-hydrogen cell technology to the point of diminishing returns with respect to improvements in weight and volume energy density and cost reduction obtainable from manipulation of the cell configuration. The most important areas for further improvement are life and reliability which are governed by electrode and separator technology.

AF NI/H2 BATTERY DEVELOPMENT APPROACH

EMPHASIS

- CELL DESIGN
- CELL TEST
- SPACE EXPERIMENT
- MANUFACTURING TECHNOLOGY
- STANDARD COMPONENTS SYSTEM

MODERATE EFFORT

- ELECTRODES
- SEPARATORS

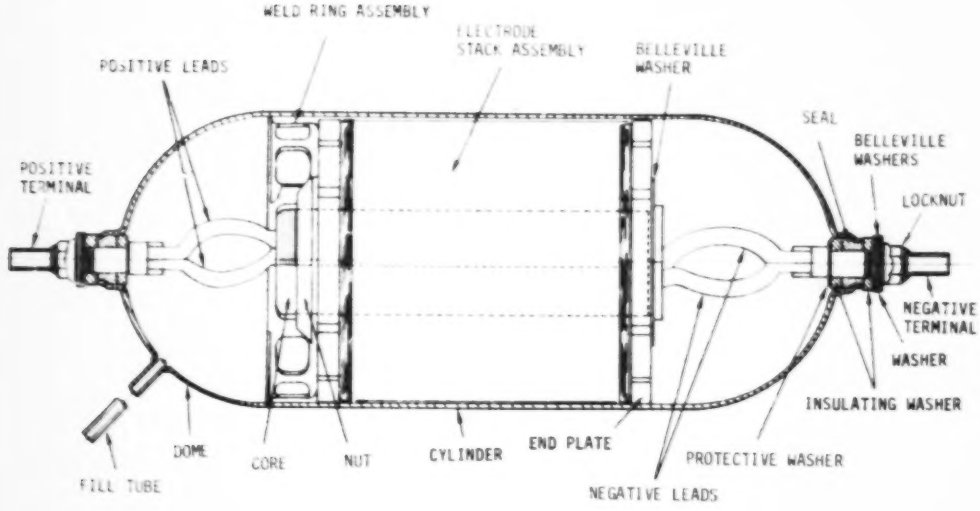
LITTLE EFFORT

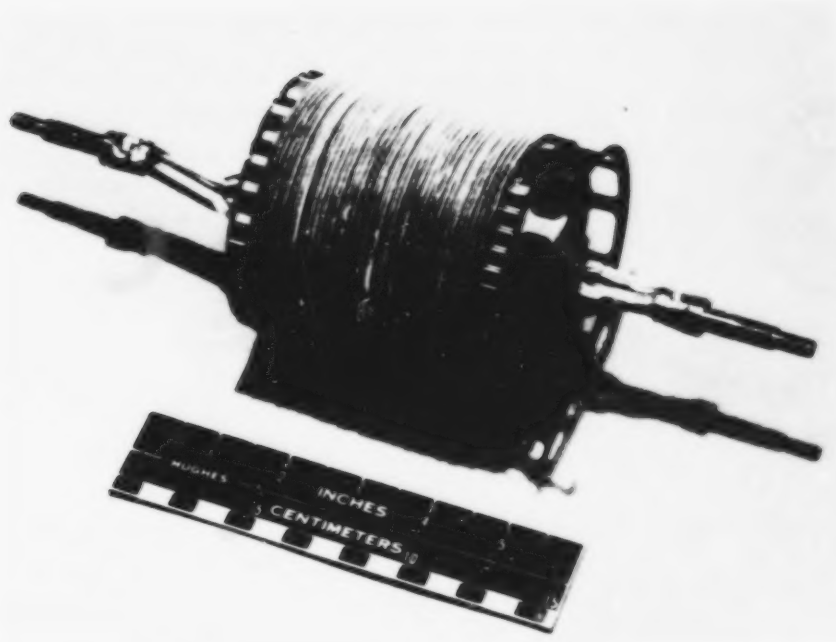
- BATTERY DESIGN
- CHARGE CONTROL

AF NI/H2 BATTERY DEVELOPMENT FEATURES

• ALL ORBIT CAPABILITY	- UP TO 80% DOD IN LOW ORBIT
• GOOD HEAT REJECTION IN ALL SIZES	- ANNULAR STACK GEOMETRY
• 0-150 AMPERE-HOURS	- TWO DIAMETERS, VARIABLE LENGTH
• OXYGEN MANAGEMENT	- OXYGEN RECIRCULATION STACK DESIGN
• ELECTROLYTE MANAGEMENT	- WICK RETURN TO STACK
• NO ELECTRODE SWELLING	- ELECTROCHEMICAL IMPREGNATION
• SHORT PROTECTION	- ETCHED FOIL NEGATIVE SUBSTRATE
• CHEMICAL & THERMAL STABILITY	- ZIRCONIUM-OXIDE CLOTH SEPARATOR
• SINGLE PRESSURE VESSEL WELD	- HYDROFORMED SHELLS, HYDRAULIC SEAL
• STANDARD COMPONENTS SYSTEM	- TWO CELL DIAMETERS, TWO CONFIGURATIONS

NI/H2 CELL SCHEMATIC

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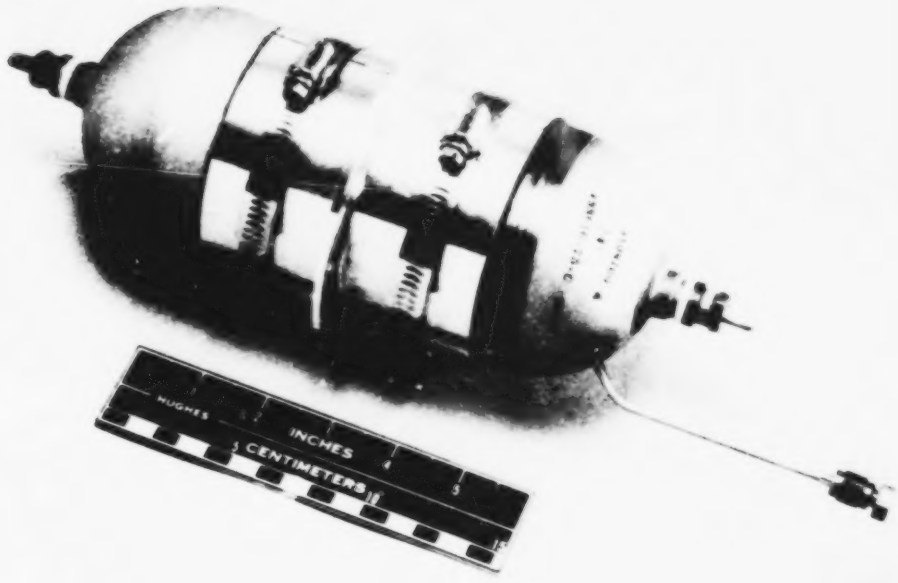
CENTIMETERS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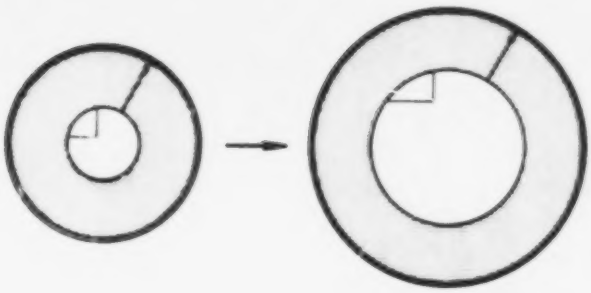
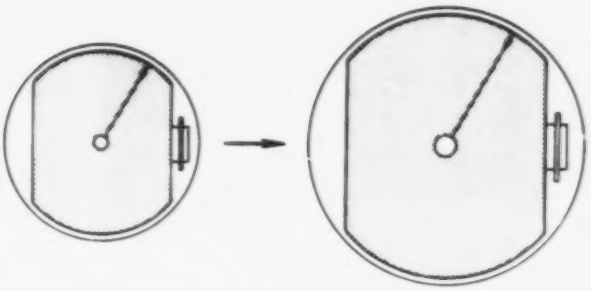
GOOD HEAT REJECTION IN ALL SIZES



ANNULAR ELECTRODE (CHOSEN)

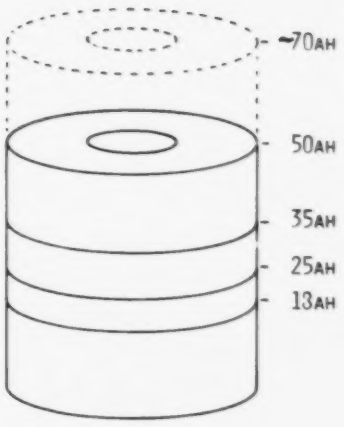
- SHORT HEAT TRANSFER PATH
- UNIFORM GAP TO PRESSURE VESSEL
- LARGER SIZES:
  - HEAT TRANSFER DISTANCE ~SAME
  - $\left[\frac{\text{WASTE HEAT}}{\text{HEAT TRANSFER AREA}}\right]$ STAYS SAME



TRUNCATED DISC ELECTRODE

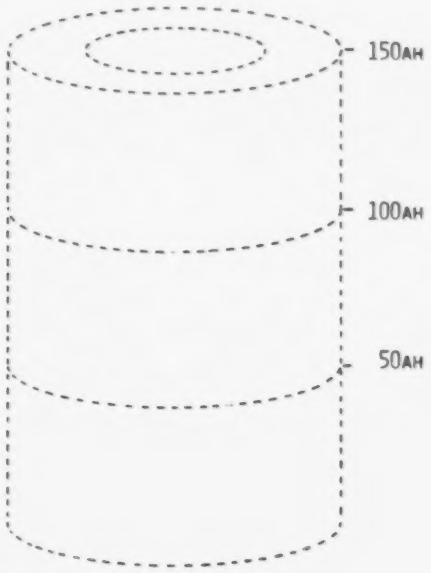
- LONGER HEAT TRANSFER PATH
- CUTOUTS FOR TABS AND LEADS REDUCE HEAT TRANSFER
- LARGER SIZES:
  - HEAT TRANSFER DISTANCE INCREASES
  - $\left[\frac{\text{WASTE HEAT}}{\text{HEAT TRANSFER AREA}}\right]$ INCREASES

TWO STANDARD DIAMETERS - TWO CAPACITY RANGES



3.5 INCH DIAMETER

ALL CAPACITIES USE SAME COMPONENTS

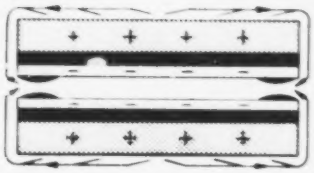


4.5 INCH DIAMETER

ALL CAPACITIES USE SAME COMPONENTS

OXYGEN MANAGEMENT

RECIRCULATION STACK



BACK-TO-BACK STACK

RECIRCULATION STACK (CHOSEN)

- SHORT OXYGEN PATH
- LARGE OXYGEN RECOMBINATION AREA
- RECOMBINATION HEAT AND WATER EVENLY DISTRIBUTED OVER NEGATIVE ELECTRODE

NEGATIVE ELECTRODE

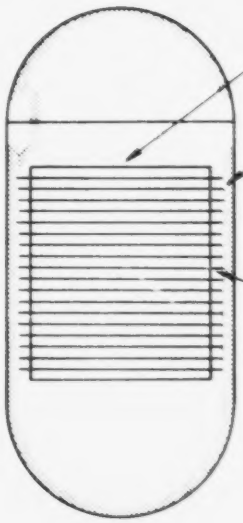
- TEFLON BACKING HIGHLY PERMEABLE TO OXYGEN

RELATED FACTORS

- RECIRCULATION STACK REQUIRES RECIRCULATION SYSTEM
- RECIRCULATION SYSTEM CONTRIBUTES TO ELECTROLYTE AND THERMAL MANAGEMENT

ELECTROLYTE MANAGEMENT SYSTEM

RECIRCULATION SYSTEM



RECIRCULATION STACK

- REQUIRES RECIRCULATION SYSTEM

WALL WICK

- ZIRCONIUM-OXIDE COATING ON INSIDE OF PRESSURE VESSEL
- EXCESS ELECTROLYTE PROVIDED
- MAINTAINS ELECTROLYTE BALANCE WITHIN STACK
- RETURNS ELECTROLYTE TO STACK

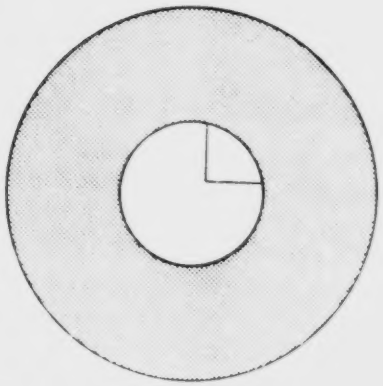
SEPARATORS

- DISTRIBUTE ELECTROLYTE BETWEEN WALL WICK AND ELECTRODES

RELATED FACTORS

- RECIRCULATION SYSTEM CONTRIBUTES TO THERMAL MANAGEMENT

POSITIVE ELECTRODE



ELECTROCHEMICAL IMPREGNATION

- DIMENSIONAL STABILITY
- BETTER UTILIZATION OF ACTIVE MATERIAL
- LONGER LIFE
- LOWER COST WHEN PRODUCTION IS ESTABLISHED

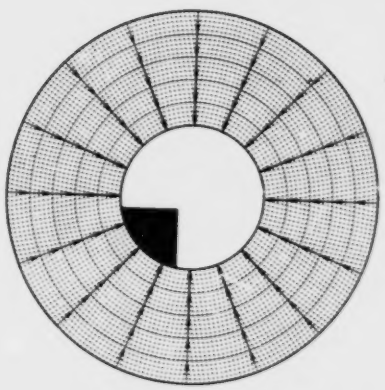
NICKEL SCREEN SUBSTRATE

- COLD WELDED TO ELIMINATE LOOSE WIRES

EDGE PROTECTION

- COINED BOTH SIDES
- POLYSULFONE COATED

NEGATIVE ELECTRODE



TYPE

- TEFLON BONDED - PLATINUM CATALYST

PHOTOCHEMICALLY ETCHED NICKEL FOIL SUBSTRATE

- DIMENSIONALLY STABLE
- NO LOOSE WIRES TO CAUSE SHORT CIRCUITS
- LOWER VOLTAGE DROP
- BETTER TAB WELDS

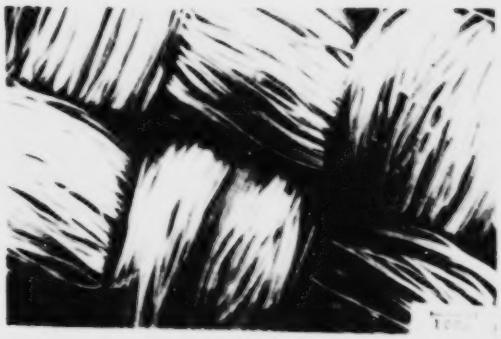
PROBLEM

- OCCASIONAL FLOODING

POTENTIAL SOLUTIONS

- WASH OUT RESIDUAL WETTING AGENTS
- CHANGE SINTERING TEMPERATURE
- CHANGE TEFLON CONTENT
- CHANGE PORE SIZE OF TEFLON BACKING

SEPARATOR



ZIRCONIUM OXIDE CLOTH

- THERMALLY STABLE
- CHEMICALLY STABLE
- INTRINSICALLY WETTABLE
- DUAL POROSITY AIDS ELECTROLYTE MANAGEMENT
  - FIBER BUNDLES HOLD ELECTROLYTE TIGHTLY
  - VOIDS PROVIDE RESERVOIR ACTION

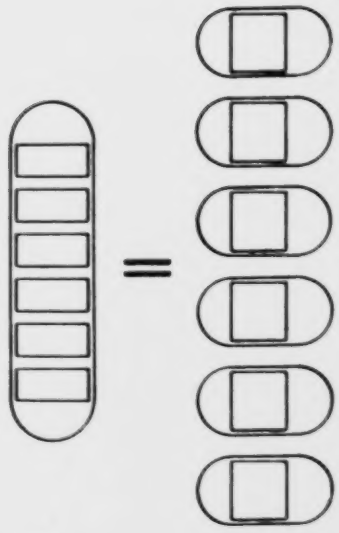
PROBLEM

- ON OVERCHARGE – OXYGEN PASSING THROUGH SEPARATOR AND RECOMBINING ON NEGATIVE CAN CAUSE LOCAL HOTSPOTS THAT CAN MELT PINHOLES IN NEGATIVE

POTENTIAL SOLUTION

- REDUCE OXYGEN PERMEABILITY WITH COATING

COMMON PRESSURE VESSEL NI/H2 BATTERY



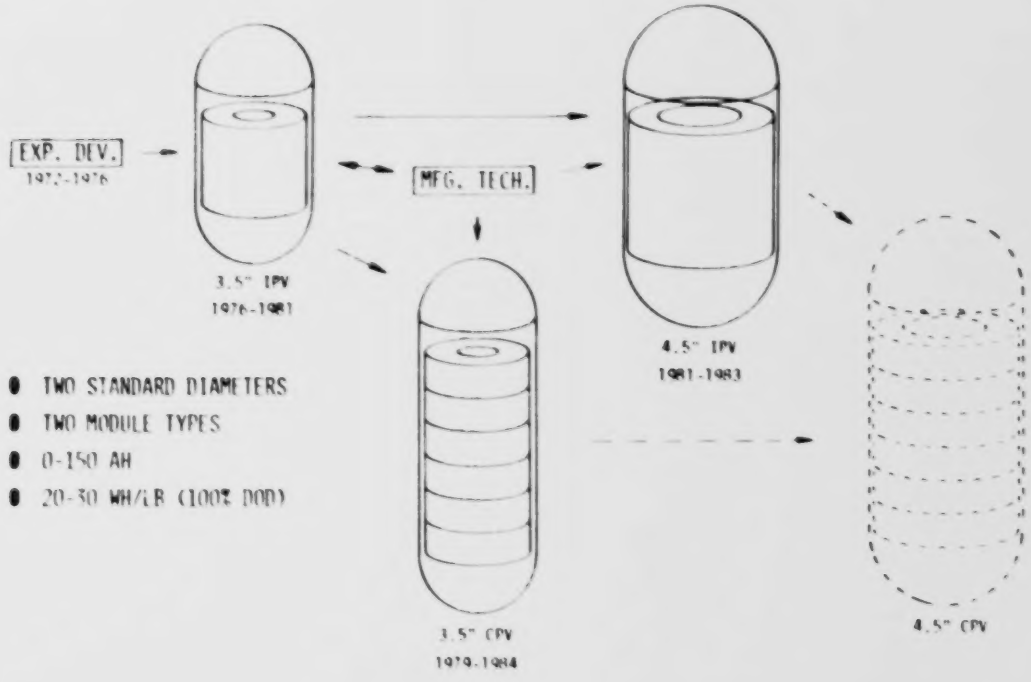
ADVANTAGES:

- 40% VOLUME REDUCTION
- 30% COST REDUCTION
- 20% WEIGHT REDUCTION

PROBLEMS:

- ELECTROLYTE BRIDGING BETWEEN CELLS
- INTERCELL CONNECTIONS
- INTERCELL VAPOR TRANSFER

NI/H2 BATTERY STANDARD COMPONENTS SYSTEM



- TWO STANDARD DIAMETERS
- TWO MODULE TYPES
- 0-150 AH
- 20-30 WH/LB (100% DOD)

FURTHER DEVELOPMENT REQUIRED

SEPARATOR

- REDUCE OXYGEN PERMEABILITY

NEGATIVE ELECTRODE

- ELIMINATE FLOODING
- REDUCE PLATINUM CONTENT

POSITIVE ELECTRODE

- TECHNOLOGY IMPROVEMENT
- DEVELOP ACCELERATED SCREENING TESTS

PRESSURE VESSEL

- RELOCATE TERMINALS TO REDUCE VOLUME 30%
- REDUCE COST OF GIRTH WELD

BATTERY DESIGN (WITH CELL REDUNDANCY)

CHARGE CONTROL

CELL AND BATTERY LIFE TESTING

N80-33475

POWER MANAGEMENT

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National Aeronautics and Space Administration
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TECHNOLOGY FOCUS:

- SPACE PLATFORM IN LEO
- 250 kW (AVG.) CONTINUOUS LOAD POWER
- PRIME GENERATOR - SOLAR ARRAY
- MID-1980 TECHNOLOGY READINESS/LATE 1980 IOC
- TEN YEAR LIFE
- SHUTTLE LAUNCH
- ON-ORBIT MAINTENANCE/REPAIR/RETRIEVAL CAPABILITY
- LOW LIFE CYCLE ENERGY COST

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OBJECTIVE/APPROACH

The objective of the multihundred kW power system management and distribution program is to develop the critical components, circuits and subsystems required to manage the generation, storage, and distribution of energy in large, orbital space systems. The approach taken to accomplish this objective is to design a reference system including the generation, energy storage, electrical power management and thermal energy management subsystems. This reference design is then used to assess at the system level the impact of changing various subsystem parameters. Based on the reference system design, a detailed design of the power management subsystem will be performed. The power management subsystem is autonomous and based on ground utility power systems concepts to the maximum extent possible. An agency power system breadboard is being developed for characterization and verification of the various component and subsystem technology developments.

OBJECTIVE:

- DEVELOP CRITICAL COMPONENTS, CIRCUITS, AND SUBSYSTEMS REQUIRED TO MANAGE THE GENERATION, STORAGE, AND DISTRIBUTION OF ENERGY IN LARGE SPACE SYSTEMS.

APPROACH:

- PERFORM REFERENCE SYSTEM DESIGN
  - GENERATION
  - ENERGY STORAGE
  - ELECTRICAL POWER MANAGEMENT
  - THERMAL ENERGY MANAGEMENT
- DEVELOP POWER MANAGEMENT AND DISTRIBUTION SUBSYSTEM FOR MULTI-100 kW ORBITAL POWER PLANT.
- PROVIDE AN AGENCY BREADBOARD FOR COMPONENT AND SUBSYSTEM CHARACTERIZATION AND VERIFICATION.

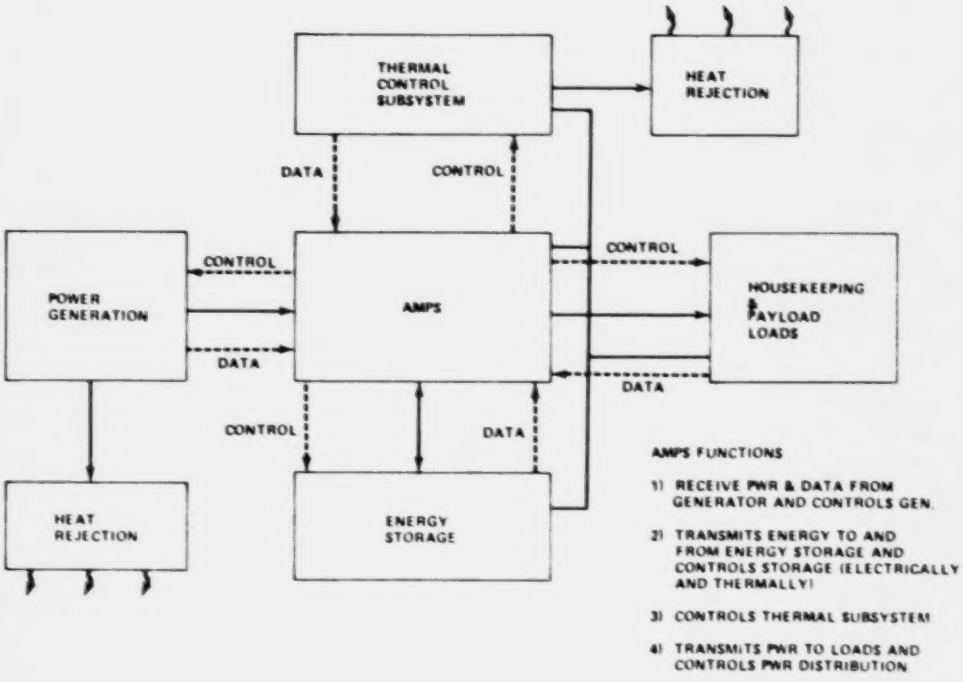
AMPS INTERFACES:

On this page is a block diagram depicting the major elements of the power system technology program and their key interfaces. As can be seen, the heart of the system is the power management and distribution element which is tilted the autonomously managed power system (amps). The various functions of the amps in relation to the other major elements are listed. For instance, the power generation system can be monitored and controlled to optimize its performance. For a photovoltaic system this might include solar pointing functions as well as on-array regulation and/or conditioning of power.

In the energy storage subsystem, capability will exist for utilization of various energy storage elements in direct proportion to their state-of-health. If secondary batteries are used, the generation of an appropriate signal can tell the amps control center that a different recharge fraction, different charge cutoff voltage, or different operating temperature for a particular battery (or battery module) would improve overall system performance.

Thermal control of the entire spacecraft is implemented by amps through appropriate sensing, logic, and control signal initiation.

AUTONOMOUSLY MANAGED POWER SYSTEM



SCHEDULE:

A BRIEF OVERVIEW OF THE PROGRAM SCHEDULE WITH SOME OF THE MAJOR MILESTONES LISTED IS SHOWN ON THE FACING PAGE. SPECIFIC PROGRAM TARGETS INCLUDE:

(1) COMPLETION OF REFERENCE SYSTEM BASELINE AND ESTABLISHMENT OF TECHNOLOGY RISK FOR THE VARIOUS OPTIONS IDENTIFIED BY MID-FY 1981.

(2) DEVELOPMENT OF CRITICAL CIRCUIT AND SUBSYSTEM TECHNOLOGIES REQUIRED FOR MANAGEMENT OF MULTI-100 KW POWER SYSTEMS BY THE END OF FY 1983.

(3) DEMONSTRATION OF AUTOMATED POWER SYSTEM MANAGEMENT BY THE END OF FY 1983.

SCHEDULE

SYSTEM DEFINITION

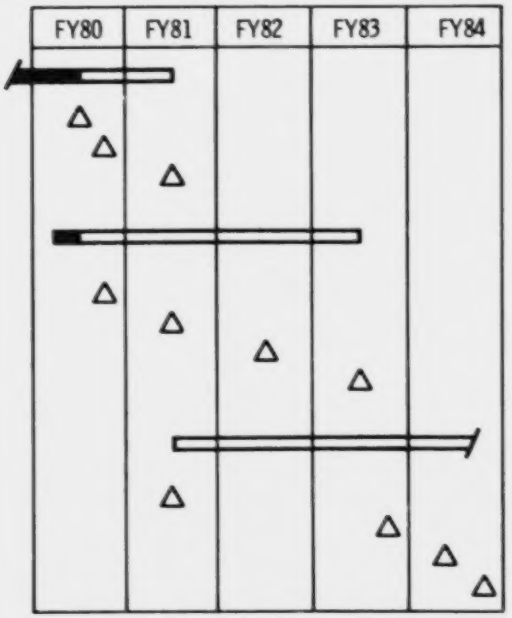
- TRADES COMPLETE
- REFERENCE EPS COMPLETE
- ROI COMPLETE

AMPS DEVELOPMENT

- COMPONENT TECHNOLOGY ASSESSMENT
- ESTABLISH THERMAL MGMT. REQTS.
- COMPLETE DESIGN
- AMPS BREADBOARD ASSEMBLY COMPLETE

BREADBOARD DEMONSTRATION

- COMPLETE SYSTEM BREADBOARD MODS.
- AMPS INTEGRATION COMPLETE
- VERIFICATION COMPLETE
- AMPS TECHNOLOGY READINESS



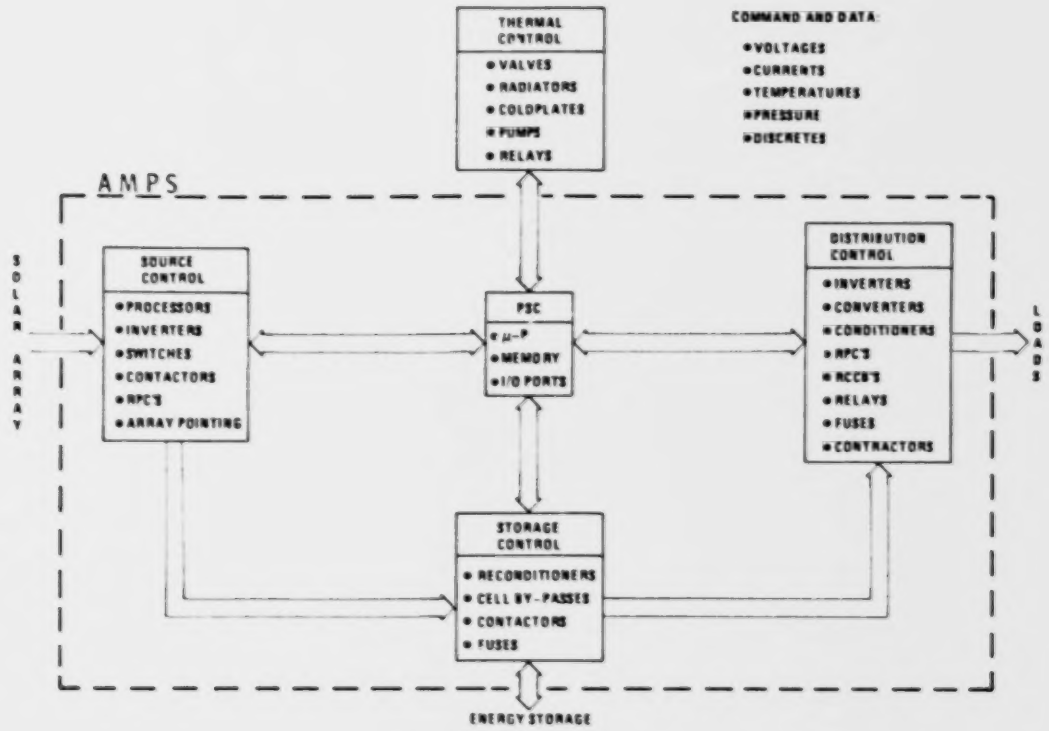
AMPS FUNCTIONS

As depicted on the facing page, the amps performs five basic functions:

(1) Total power system management
(2) Source control
(3) Energy storage control
(4) Thermal system management
(5) Distribution control

The components and equipment required to accomplish the implementation of each function is listed. Based on the reference power system concept selected, detailed design requirements for each component or piece of equipment will be generated, and the required technology developments identified.

POWER SYSTEM MANAGEMENT
AND DISTRIBUTION



COMPONENT TECHNOLOGY DEVELOPMENTS:

A preliminary list of component technology developments based on proposed concepts and assessments made to date is shown. A list of component developments required for the selected eps concept and reference design will be an output of the component technology assessment task.

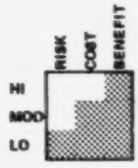
COMPONENT TECHNOLOGY DEVELOPMENTS:

DEVELOPMENT ITEM	PRIMARY CHARACTERISTICS
RPC	300 VDC, 100 A
SOLID STATE CKT. BREAKER	300 V, 1 - 20 A 300 V, 50 - 200 A
VACUUM SWITCH	300 V, 200 A
ON-ARRAY SWITCHING DEVICES	XSISTOR - 300 V, 10 A MICROPROCESSOR DATA BUS
SLIP RINGS ROTARY TRANSFORMER	300 V, 400 A
CONNECTORS	300 V, 200 A

AMPS BREADBOARD VERIFICATION OBJECTIVES:

- Establish transient response to load switching
- Verify fault detection and clearing
- Measure system efficiencies for various operating modes
- Estabish and verify power quality standards
- Demonstrate utility power management and distribution concept
- Evaluate new component technologies in a realistic environment

DEVELOPMENT RECOMMENDATIONS*



- HIGH VOLTAGE BUS AND COMPONENTS (100 - 300 V)

- AUTOMATED POWER SYSTEM UTILIZING ON-BOARD FAULT DETECTION AND CORRECTION TO MINIMIZE GROUND SYSTEM COST

- HIGH VOLTAGE BUS AND COMPONENTS (300 V - 1 KV) IN WHICH USE OF ALTERNATING CURRENT MAY BE ATTRACTIVE

*SOURCE: SYMPOSIUM ON POWER TECHNOLOGY FOR FUTURE SYNCHORONOUS SATELLITES AND PLATFORMS, MAY 1979.

CONCLUSION

- The amps program for LEO technology in the 250 kW category includes all specific technology and development activities recommended by the "power technology for future synchronous satellites and platforms symposium" of May 1979 except fiber optics

RECOMMENDATION

- The amps program be augmented to the extent that breadboard testing include GEO mission profiles and unique operating parameters.

TECHNOLOGY RECOMMENDATIONS*

- DEVELOP RELAYS, FUSES, AND SOLID STATE SWITCHES TO DISTRIBUTE POWER TO MULTI-KW LOADS IN 100 TO 400 VOLT SYSTEMS WITH CURRENTS IN THE 100 AMPERE RANGE.
- DEVELOP AND QUALIFY A RADIATION HARDENED POWER SUBSYSTEM CENTRAL PROCESSOR INCLUDING SOFTWARE IMPLEMENTATION OR BATTERY CHARGE CONTROL, LOAD MANAGEMENT, POWER SYSTEM STATE OF HEALTH MONITORS AND CONTROL AND TELEMETRY CONDITIONING.
- REDUCE CABLING WEIGHT BY FLIGHT QUALIFICATION OF 100 - 500 V SOLAR ARRAYS AND 100 - 300 V BATTERIES.
- REDUCE RF AND SIGNAL CABLING WEIGHT THROUGH THE USE OF FIBER OPTICS.
- REDUCE POWER CONDITIONING AND DISTRIBUTION EQUIPMENT WEIGHT BY ADVANCING THE STATE OF THE ART OF HIGH FREQUENCY/HIGH VOLTAGE/HIGH POWER CONVERSION AND CONTROL EQUIPMENT.

*SOURCE: SYMPOSIUM ON POWER TECHNOLOGY FOR FUTURE SYNCHRONOUS SATELLITES AND PLATFORM, MAY 1979.

INTRODUCTION TO WORKSHOP REPORTS

This section is the output of the four workshop groups at the Symposium: Photovoltaics, Thermal Management, Energy Storage, and Power Management,

The Symposium/Workshop resulted from an action of the AFSC/NASA-OAST Interdependency Working Group to define a cooperative program between the Air Force and NASA in the field of synchronous and high-altitude, high-power system technology. Workshops were composed of technologists expert in one of the four disciplines. As proposed to each workshop, their objectives were to

(1) Establish a set of technology goals and requirements for a representative high-power, geosynchronous power system
(2) Review the goals and status of applicable on-going technology programs
(3) Identify those technologies not presently underway which would be required for the defined system
(4) Establish goals and resource requirements for the identified new technology activities
(5) Define program roles and responsibilities.

Suggested questions related to these objectives were provided to each workshop chairman for discussion within his group.

The format for workshop writeups was not standardized and reflect, to some degree, the technical difficulties each group had in dealing with synchronous-energy technology constraints. Storage and thermal management emerged as the areas most in need of technology advancement.

In general, the workshop information presented here represents the views of the members as expressed by the Chairman and has not been edited. This information will be used to define the scope and characteristics of a potential NASA/AF joint technology program.

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PHOTOVOLTAICS WORKSHOP[1]

RESPONSE TO GUIDELINE QUESTIONS

1. Comment on the mission model presented. - There was little discussion of the validity of the proposed mission model; it was felt that, to date, little need has surfaced to direct attention to 25-kW systems. DOD felt that if such a system was available, it would be used particularly for radar systems. High power capabilities would also benefit communication systems and could result in power platforms.

2. Identify technology goals and their time frames to meet program requirements. - Most technologies required to achieve a 25-kW low-mass, low-cost solar array system are being developed. Specific technology goals include development of solar arrays with greater than 350 W/kg by 1985, high specific power to mass gallium arsenide (GaAs) solar cells by 1985, and concentrators for LEO and GEO by 1988. The members declined to set time goals for radiation shielding (encapsulant) to protect solar cells, high voltage arrays, and high efficiency (greater percent radiation resistance) solar cells.

3. Comment on adequacy of the on-going technology programs. - It is doubtful that the level of funding designated for the development of these technologies to a state of flight readiness by the mid-1990's is adequate.

4. Define the elements of your present program which will meet the technology goals. - High power to mass solar cells and blankets are progressing to a point of flight readiness. Concentrators for LEO appear to be reasonably understood and could reach technology readiness by mid-1980. A basic understanding of GaAs solar cells will be reached by mid-1980.

5. Identify new technology (if any) required for the program. -

Set Technology Objectives - Needed:

. Develop a long-life interconnect for flexible array substrates.

. Develop reliable welding procedures and equipment for production capability, considering sonic, laser, parallel gap, etc., welding techniques.

. Explore lightweight and low cost payoff potentials from concentration, for both silicon and GaAs.

[1]All resource and schedule information are committee recommendations and do not reflect any commitment by NASA or by the Air Force.

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. Develop pilot line production capability for CVD/VPE GaAs solar cells. Start in 1985.

. Determine feasibility of solar array assembly in low orbit and transfer to synchronous orbit. If feasible develop a solar array structure compatible with that procedure.

Set Technology Objectives - Ongoing:

. Encapsulation technology efforts for light-weight flexible arrays should be augmented.

. Develop high voltage (100 to 400 V) arrays; augment.

. Develop thin GaAs solar cells; augment present effort.

. Develop radiation tolerant silicon solar cells.

. Characterize GaAs cells as regards annealing, radiation tolerance, temperature effects, and concentration.

. Develop AC model of solar arrays.

b. Estimate any delta resources ($ and MY) that may be required to address the program requirements. -

(1) Solar array structures for LEO assembly	$1 M/yr for 3 yr
(2) Si and GaAs concentration	$500 k/yr for 1-1/2 yr
(3) CVD/VPE GaAs pilot line	$750 k/yr for 3 yr
(4) Welding of solar cells	$300 k/yr for 4 yr
(5) Interconnects (weld/flex)	$100 k/yr for 4 yr

WORKSHOP PARTICIPANTS

Harry Killian (Cochairman)	Aerospace Corp.
Walter A. Hasbach (Cochairman)	Jet Propulsion Laboratory
Joseph Wise	Air Force Wright Aeronautical Laboratory
Henry Brandhorst	NASA Lewis Research Center
A. F. Forestieri	NASA Lewis Research Center
Lynwood P. Randloph	NASA Headquarters
Ed Conway	NASA Langley Research Center
Edward Gaddy	NASA Goddard Space Flight Center
S. V. Manson	NASA Headquarters
John Scott-Monck	Jet Propulsion Laboratory
William L. Crabtree	NASA Marshall Space Flight Center
William Kisko	NASA Headquarters
William E. Bachman	Jet Propulsion Laboratory

Estimated Funding ($M) to Implement Technology Recommendations

		FY						
		81	82	83	84	85	86	Total
NEEDED (New)	(1) & (2)	0.12	0.13	0.13	0.12			0.5
	(3)		0.5	0.25				0.75
	(4)				0.67	0.67	0.66	2.0
	(5)	0.2	1	1	1	---	---	3.2
	Total	0.32	1.63	1.38	1.79	0.67	0.66	$6.45 M
ONGOING (Augmentation)	(a)	0.25	0.25					
	(b)	0.20	0.10					
	(c)	0.16	0.17	0.17				
	(d)	----------as is----------						
	(e)	----------as is----------						
	(f)	----------as is----------						
	Total	0.61	0.52	0.17				1.3M
	TOTAL	0.93	2.15	1.55	1.79	0.67	0.67	$7.75M

Numbers and Letters correspond to Technology Objectives Listed Previously

THERMAL MANAGEMENT WORKSHOP[1]

WORKSHOP OBJECTIVES

The purpose of the thermal management workshop was to review the envisioned NASA and Air Force needs for higher power synchronous energy systems and to translate those needs into specific time oriented thermal management development objectives. Further objectives were to evaluate present and ongoing NASA and Air Force efforts in thermal management, identify common and agency unique "thermal show stoppers," and recommend cooperative interagency responsibilities in implementing the development objectives.

WORKSHOP FINDINGS

Based on the synchronous mission models and system concepts described in the general sessions of the SET workshop, the thermal management workshop participants formulated the following generalized mission constraints. The synchronous power and thermal management requirements for NASA will probably be driven by a large (25 to 40 kW) GEO-communication mission, based on favorable economy of scale versus ground station cost reduction and life cycle cost trades. The Air Force high power synchronous missions in the same power regime would likely be a large surveillance (25 to 50 kW) platform (e.g., radar, LWIR). Both mission categories are envisioned to be operational by the late 1980's or early 1990's, thus requiring technology-ready status by the mid-1980's. The NASA communication mission will require long life (up to 20 yr) to permit favorable revenue return per investment amortization. The Air Force surveillance mission would likely require at least 5 years of operational life. The NASA mission will be paced by cost and investment payback; the Air Force mission will not be so heavily constrained by direct cost. It will be justified by the national security value of the mission and must be designed to be survivable to hostile action.

While both large solar and nuclear reactor power systems will likely be used in both Air Force and NASA future space missions, the TM panel addressed only a solar powered mission configuration for the early IOC under consideration. This assumption was consistent with other baseline configuration assumptions by other panels.

The key common design driver for both the military and civilian missions is payload throw weight limitation to geosynchronous orbit. For the 1990 IOC date, the IUS or dual IUS propulsion capability limits the spacecraft weight to approximately 6000 to 8000 lbm. Solar electric propulsion

[1]All resource and schedule information are committee recommendations and do not reflect any committment by NASA or by the Air Force.

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spiral out payload delivery was not considered because of array degradation penalties.

With these generalized mission constraints defined, the major thermal management design problems unique to the geosynchronous missions were then addressed by the panel.

GEO UNIQUE THERMAL MANAGEMENT CONSTRAINTS

The geosynchronous military and civilian missions introduce challenging thermal management design problems. The key AF/NASA common design problem are weight, scale, contamination, and spacecraft charging.

Weight

Using current spacecraft design weight allocation fractions, the power system (25 percent) and thermal control system (10 percent) represent about 35 percent of the spacecraft weight. Hence, for a 25-kW EOL, 6000-lb spacecraft, the power system allocation is 1500 lb, and the thermal control system weight allocation is 600 lb. These translate to approximately 17 W_e/lb and 40 W_t/lb electric and thermal system performance goals. When the thermal system is composed of a thermal acquisition and control subsystem, a thermal transport system, and a thermal radiator subsystem, each of these generic subsystems must be designed to provide approximately 120 W_t/lb performance to meet the 10 percent thermal management weight allocation goal. By way of example, this performance goal represents a four-fold weight density reduction for spacecraft radiator technology. One immediate way suggested by the thermal management workshop members to improve radiator weight is to reexamine current radiator micrometeriod penetration design practice and redefine a more realistic model for the geosynchronous orbit.

Scale

The thermal management high power and geometric scale associated problems are being addressed in part by the recently implemented NASA "Thermal Utility System for High Power Spacecraft" Development Thrust. These efforts, addressing thermal control design problems and technology for an LEO 25 kW platform must be adapted to the weight sensitive, direct orbit insertion, volume limited geosynchronous missions. The workshop members concluded that the LEO platform thermal management plan fully supported the GEO application technology needs.

Contamination and Charging

Contamination outgassing and spacecraft charging problems of thermal control surfaces are also common generic problems to both the Air Force and NASA, presently being examined by the joint NASA/AF "SCATHA" program. The results of this program will likely yield substantial information on stability and conductivity requirements for improved thermal control coatings. Military thermal control coating may also have an additional laser survivability design requirement imposed.

Life

The life problem takes on two distinctly different aspects: military survivability and 5- to 10-year design life and civilian/commercial 10- to 20-year cost payback design goals. Present long life, sun-facing thermal control coating radiative property degradation problems impose a major design life problem. The ultraviolet radiation and deep space sink temperature at geosynchronous introduce stability and deep thermal cycle life problems which are not incurred at LEO. A 10- to 20-year life pump appears infeasible; heat pipe life data beyond a few years are not available. Long life power systems will require tighter thermal control on the battery in order to maximize charge efficiency and cycle life; hence, a zero heat rejection capability is envisioned for the battery and perhaps other thermally sensitive electronic or optical components.

A higher temperature radiator (25° to 50° C) will be required for other loads in order to meet overall weight goals. It is probable that both military and civilian GEO spacecraft will have multiple radiators - one for life enhancement and one for routine, higher temperature heat rejection.

The military spacecraft, in order to be survivable, might have to be maneuverable, hence, the radiator might have to be retractable and some internal transient payload waste heat absorption scheme employed.

RECOMMENDED AGENCY ROLES AND RESPONSIBILITY

Based on the common and divergent thermal management problems for civilian and military geosynchronous application described above, the following lead agency responsibilites are suggested.

It was recommended that NASA assume the lead organization responsibility for heat-pipe technology, with emphasis on scale, life, and performance enhancing research. The Air Force will adapt the generic heat pipe technology developed by NASA to specific military spacecraft heat pipe application problems, that is, thermal management of cryocooler/LWIR sensor packages.

It was further recommended that the NASA lead the development in high performance (lightweight) thermal acquisition, transport, and radiator technologies. The Air Force will concentrate on survivability oriented and geometric adaptations of these developments.

The workshop members recommended that both the NASA and Air Force continue complementary thermal control coating development efforts, with the NASA efforts concentrating on long life UV stability and electrical conductivity improvements and the Air Force efforts concentrating on survivability coatings.

Power subsystem thermal management developments are also recommended. Battery and electronic power processing thermal control technology develop-

ment should be lead by NASA. Thermal control of planar and low-cost, high-performance, concentrating photovoltaic systems should be lead by NASA; the Air Force should pursue laser hardened concentrating systems.

These recommendations imply significant future manpower and resource committments by both agencies. The method of implementation is considered to be a substantial planning and management commitment task beyond the scope of this workshop's responsibilities.

SPECIFIC GEO THERMAL MANAGEMENT THRUSTS

In response to the high power GEO thermal management technology needs described in the previous sections, seven recommended programmatic thrusts were identified. These are

- GEO-1 - Mission requirements study
- GEO-2 - Long life thermal control coatings development
- GEO-3 - High-voltage, high-power-density electronic cold plate development
- GEO-4 - 25-kW concentrator array electrical/thermal design study
- GEO-5 - Lightweight high effectiveness radiator development
- GEO-6 - Large thermal control antenna
- GEO-7 - Pulse power systems thermal management

The following paragraphs outline the purpose and scope of each of these programmatic thrusts. Total yearly funding breakouts of NASA and Air Force resources are shown in table I. Table II shows, by comparison, ongoing and supportive NASA Thermal Management R&D activities which are not directly related to the high power GEO applications problem.

GEO-1 - Mission Requirements Study

The purpose of this study is to define the general spacecraft configurational and environmental design constraints for the high power GEO communications and surveillance missions of interest. The study will include an assessment of the validity of the present NASA micrometeroid model and design radiator design weight penalties associated with that conservative model. Thermal control coating degradation design penalties on solar array and spacecraft radiators will also be assessed, as well as EOL/BOL radiator effectiveness variation schemes to improve thermal control regulation limits. Payload electronic component packaging layouts and thermal acquisition/transport/radiator interface schemes will be assessed to define critical design and development issues, including high-power-density waste-heat components (e.g., TWT's) and low temperature thermal control components. The study output will provide generalize environmental and performance objectives design data for follow-on technology development efforts. Recommended funding is

FY 81	FY 82
$150 k	$100 k

GEO-2 - Long Life Thermal Control Coatings Development

This task is motivated by a continuing need to improve the radiative properties and stability of thermal control surfaces. Present UV induced coating degradation to 25% required oversizing the spacecraft radiator by a similar amount. The purpose of this task is to augment development resources for conventional coatings and explore novel, nonconventional approaches. Desirable funding levels are

FY 81	FY 82	FY 83	FY 84	FY 85
$250 k	$250 k	$300 k	$300 k	$200 k

GEO-3 - High Voltage, High-Power-Density Cold Plates

Use of high voltage (100 to 600 V) power systems on satellites and the compactness of modern power conditioning and electronic equipment combine to require development of special cold plates to remove waste heat from critical components. Presently available circuit boards with miniature heat pipes can transfer about 0.1 W/cm^2. This must be increased at least an order of magnitude in local areas either by developing better heat pipes or by "spreading" the thermal flux using high thermal conductance materials. Cold plates may be required for two different temperature ranges (e.g., 0 to 20° C and 40° to 65° C) so that overall system efficiency is maximized. The cold plates should be designed to minimize component temperature variations within the operating range so that reliability is improved. A program to develop the needed cold plates should be started early to provide time for extended experiments and determination of long term materials compatibility. Laboratory operation of final cold plate configurations with simulated heat loads would demonstrate technology availability. The work could possibly be included as part of the Instrument Module Heat Transport System program being proposed by Goddard Space Flight Center. Recommended funding for the cold plate work is as follows:

FY 81	FY 82	FY 83	FY 84	FY 85	Total
$40 k	$100 k	$150 k	$150 k	$100 k	$540 k

GEO-4 - 25-Kilowatt Concentrator Array Electrical/Thermal Design Study

The previous NASA 250 kW Power Modules studies for LEO applications need to be reassessed for the revised 25- to 40-kW GEO design point. In reiterating the design studies, it is suggested that careful comparisons of planar arrays, with periodic thermal annealing, be compared with passively (conductively) cooled low-concentration-ratio and actively cooled, high-concentration-ratio designs. In order to achieve a power system performance goal of 17 W_e/lb, it appears that the EOL array performance must exceed 50 W_e/lb, based on approximately equal weight fractions of the array, battery, and power processing components. Required funding for this task is

FY 81	FY 82	FY 83
$200 k	$200 k	$400 k

GEO-5 - Lightweight, High Effectiveness Radiator

Extensive development is needed to provide thermal radiators having both the low weight and high effectiveness required for high power level satellites in high altitude orbits. Present technology for 20 to 30 W/kg radiators must be significantly improved to keep overall spacecraft weight within available boost capability for high altitude orbits. The radiators must also be deployable for the anticipated high power levels. Radiator work at the Marshall Space Flight Center and the Johnson Space Center can be extended for further heat pipe radiator development. Improving the thermal effectiveness of the radiators will minimize deployed area and weight. The work would be correlated with the development of improved surface coatings. Air Force special purpose programs, such as space surveillance and survivability, will also provide technology contributions. The radiator program should begin promptly to allow time for concept verification before subsystem simulation tests. Estimated funding requirements are

FY 81	FY 82	FY 83	FY 84	FY 85	Total
$150 k	$400 k	$600 k	$300 k	$200 k	$1650 k

GEO-6 - Large Thermal Control Antenna

Very large, deployable antennas will be required for future satellite communications and space-based radar systems. These large net structures, which may contain radiating elements, must have carefully controlled contours for effective operation. Temperature variations across the antenna could cause severe distortion unless proper thermal control and structural compensations are provided. Although several possible thermal control approaches, ranging from passive to active, have been conceived, no significant development work has been done. Analytical and experimental work should begin promptly to investigate appropriate structural compensations, insulation methods, and actively controlled tension systems. Both thermal and electromagnetic characteristics must be given proper consideration. Estimated funding requirements for an antenna thermal control program are as follows:

FY 81	FY 82	FY 83	FY 84	FY 85	Total
$50 k	$150 k	$300 k	$500 k	$200 k	$1200 k

GEO-7 - Pulse Power System Thermal Management

This task explores spacecraft energy and heat rejection management for those applications with large peak/average power ratios, such as antijam communication or other high pulse power military systems. Techniques to absorp or otherwise thermally integrate transient pulse power loads and reject mean low average power will be investigated. Other energy averaging thermal control techniques will be investigated to reduce parasitic heater power requirements, which can represent as much as 10 percent of the power system load. Hardware capable of 10/1 and 1000/1 peak to average load dissipation and 10/1 storage/use (base plate) thermal control will be demonstrated. Required funding estimates are

FY 82	FY 83	FY 84	FY 85
$200 k	$300 k	$400 k	$200 k

WORKSHOP PARTICIPANTS

Tom Mahefkey (Chairman)	Air Force Wright Aeronautical Laboratories
Richard Gualdoni	NASA Headquarters
Sol Gorland	NASA Lewis Research Center
Bill Haskin	Air Force Wright Aeronautical Laboratories
H. P. Lee	NASA Goddard Space Flight Center
Ira Meyers	NASA Lewis Research Center
John Oberight	NASA Goddard Space Flight Center
Gary Rankin	NASA Johnson Space Center
Jerold L. Vaniman	NASA Marshall Space Flight Center

TABLE I
GEO THERMAL MANAGEMENT
TASK FUNDING PROPOSED

MILESTONES	81	82	83	84	85
REQTS STUDY (LeRC)	$150K	$100K	-	-	-
LONG LIFE T/C COATINGS (NASA/AF)	$250K	$250K	$300K	$300K	$200K
HI VOLT., HI PWR DENSITY COLD PLATE (NASA)	$ 40K	$100K	$150K	$150K	$150K
25KWe CONCENTRATOR/ARRAY RECONDITION (NASA)	$200K	$200K	$400K	-	-
LIGHTWEIGHT, HI EFFECTIVENESS RADIATOR (NASA)	$150K	$400K	$600K	$300K	$200K
LARGE RADAR AND COMM ANTENNA T/C (NASA/AF)	$ 50K	$150K	$300K	$500K	$200K
PULSE POWER HEAT REJECTION AVERAGE (AF)	-	$200K	$300K	$400K	$200K

TABLE II
THERMAL UTILITY SYSTEM FOR HIGH POWER SPACE PLATFORMS
RESOURCE 1987 TECHNOLOGY READINESS SCHEDULE, $K (FY '80$)

# TASKS	FY '79	FY '80	FY '81	FY '82	FY '83	FY '84	FY '85	FY '86	TOTALS
THERMAL MANAGEMENT									4297
Priority #1 — 11	47	290	445	550	335	315	365	300	
Priority #2 — 5				320	380	450	500		
Priority #3 — 3									5030
THERMAL ACQUISITION & TRANSPORT									
Priority #1 — 7	75	445	650	735	825	800	300	50	
Priority #2 — 7				850	150	100	50		
Priority #3 — 1									2815
HEAT REJECTION									
Priority #1 — 4		125	250	375	180	180	100	100	
Priority #2 — 2				180	550	500	275		
Priority #3 — 4									
TOTAL	122	860	1345	3010	2420	2345	1590	450	12142

ENERGY STORAGE WORKSHOP[1]

The meeting brought out the fact that energy storage is probably the weakest of the technology areas under consideration. This was especially noticeable since it (storage) is key to the entire mission (multikilowatt in synchronous orbit). Another perceived shortcoming that became apparent as a result of the meeting was the lack of overall responsibility needed to bring into focus the thermal management-power processing-storage system interactions and interrelationships. The multitude of technology tasks in this highly fragmented area of storage technology tend not to be large enough to effectively address the problems at hand. The problems themselves are not clearly defined, and, where they are, they tend to be temporal.

HIGH ENERGY DENSITY BATTERIES (HEDB)

This category includes both primary and secondary cell and battery activity. The area of HEDB has traditionally been confined to room temperature lithium anode/organic electrolyte studies. Higher temperature systems (sodium/sulfur and lithium/metal sulfide) are also included in this class. They have always offered the potential for significant advances in energy density. The slow rate of advancement made over the past 20 years of active investigation has demonstrated the high degree of risk associated with this technology.

The safety aspects of the low temperature primary cells that have found use in the military for low to medium rate applications have somewhat restricted their application in the civilian sector. The prospects of finding the proper combination of chemical stability and electrochemical reactivity and reversibility is somewhat in doubt.

The potential of the high-temperature class of single cells that are currently under development by DOE for terrestrial applications has not been fully explored for space use. These systems will require single cell charge control and cell switching when used in a multicell battery. It would appear that the heating requirements and associated thermal management system designs may reduce the apparent high-energy densities at the cell level to the point where at the system level they would no longer be of interest. DOD and NASA are also supporting HEDB but at low funding levels. Within NASA, Lewis is working on separators for low temperature lithium cells. The Jet Propulsion Laboratory is working on the lithium-titanium disulphide and molybdenum triselenide system which shows some promise for

[1]All resource and schedule information are committee recommendations and do not reflect any committment by NASA or by the Air Force.

being rechargable. The Wright Patterson Aero Propulsion Laboratory has a contractor surveying this class of batteries and the work being done on them around the country.

FUEL CELL/ELECTROLYSIS

The use of a fuel cell system in conjunction with an electrolysis unit and the associated storage tanks represents an alternative to the more traditional cell/battery concept of energy storage. These systems can be based either on hydrogen/oxygen or hydrogen/halogen chemistries. In general the hydrogen/oxygen system has a lower round trip efficiency than the hydrogen/halogen systems. The added features of the hydrogen/oxygen system that would allow it to be integrated into the life-support subsystem of a manned type orbit does not come into consideration for the synchronous orbit mission presented to the workshop and thus the hydrogen/halogen class of system would be the logical candidate for consideration. The energy density of fuel-cell/electrolysis combinations are highly dependent on the required storage duration - much more so than for the more traditional cell/battery storage systems. This stems from the fact that the power producing and consuming portion of the system represents a more or less fixed weight and the storage related portion of the system depends on the storage duration. The requirement for circulation pumps represents a possible weak point of this class of storage device. The fact that the total hours of actual operation in this orbit is a rather small fraction of the calendar duration may not preclude the consideration of these systems for this mission, where reliability is so highly important. This type of system (H_2O-O_2-H_2O fuel-cell/electrolysis unit using SPE membrane technology) was under development in the late 1960's by the Wright Patterson Air Force Base. Detailed system designs need to carried out around a specific proposed mission before entertaining any serious system development work. The early SPE system hardware work needs to be reviewed to take into account all the improvements and advances that have occurred within this technology. The fuel-cell/electrolyzer systems can be based on either the acid ion exchange membrane technology or the alkaline matrix technology. Although it would appear that the all alkaline system have a lower overall weight, there is no one supplier of both the fuel cell and the electrolyser unit. For the higher energy density hydrogen/halogen systems, the ion exchange membrane technology appears to be more advanced in terms of materials compatibility and equipment performance. Since fuel cells and electrolyzer equipment are currently being tested and their performances only partially established, any effort towards the use of these technologies for SET applications should address a system design and weight study to identify any technology holes.

NICKEL-HYDROGEN BATTERY

Ni/H_2 batteries, where each cell is contained in its own individual pressure vessel (IPV), have been developed since 1971 by the Comsat Corporation for GEO use and by the Air Force for LEO and GEO use. These cells have a nominal 3.5-in.-diam, suitable for capacities up to about 70 A·hr. Comsat and Air Force Ni/H_2 batteries were flown successfully on separate space experiments in 1977. Both types of cells have been selected for operational missions in the early 1980's. The Air Force

program is expanding to include a manufacturing technology program on the 3.5-in.-diam IPV cells (FY 80), exploratory development of 3.5-in.-diam modules in which several cells are packaged in a common pressure vessel (CPV) (FY 79), and advanced development of 4.5-in.-diam IPV cells (FY 81). The larger 4.5-in.-diam components will allow IPV cells with capacities up to 150 A·hr, and are potentially usable in 4.5-in.-diam CPV modules although that development is not currently planned.

NASA is becoming involved in Ni/H_2 battery activity in order to contribute to a more rapid realization of the advantages offered by this technology. NASA has formed an ad hoc committee of battery specialists from the various centers to assess the state of the art, determine needs, and develop a plan for such involvement. The Energy Storage Workshop did not want to preempt the activities of the ad hoc committee with specific recommendations at this time; however, certain outlines of a possible natural division of effort between NASA and the Air Force, based on the strengths and weaknesses of the Air Force program and on special areas of NASA expertise, were discussed.

The Air Force program has emphasized the solution of cell design problems that are unique to the Ni/H_2 couple and the development of an integrated system of cell hardware whereby a wide variety of cell capacities and configurations can be assembled from a minimum number of standard, interchangeable components. The Air Force cell designs, driven by the high rate, high cycle life requirements of LEO, have special, and apparently effective, provisions for thermal management, oxygen management, and electrolyte management. The Air Force hardware configurations are the result of extensive computer aided design efforts. Although alternative designs could be developed, it is unlikely that significant gains in weight or volume energy density can be attained from configuration changes alone. The one exception to this is a redesign of the endcap/terminal assembly to reduce volume, but the Air Force has already started this activity.

INDUCTIVE ENERGY STORAGE

Inductive energy storage using superconducting coils appears capable of weight energy densities in the 20 to 30 W·hr/lb range. On the basis of this energy density alone, the risk-to-reward ratio for this technology would appear to be high compared with competing technologies. However, inductive energy storage may have unique capabilities such as indifference to depth-of-discharge and cycle life, ability to supply large quantities of energy repetitively in a very short time, and use with electric rail gun thrustors to provide rapid transit from LEO to GEO and subsequent eclipse storage in GEO.

The Air Force is involved in research and manufacturing technology programs on superconducting materials, and NASA is involved in complementary work on cryogenic technology. Both NASA and the Air Force are considering feasibility investigations of inductive energy storage that may lead to a better definition of the relative merit of such technology. The workshop elected to not make recommendations in this area in the absence of study results defining the feasibility and relative merit of such devices.

INERTIAL ENERGY STORAGE

One of two nonelectrochemical storage techniques discussed was the possible use of flywheels (the other being inductive). On the surface, this concept would appear to have a number of advantages over the more traditional single-cell/battery energy storage. A single unit would produce directly the voltage level required. The material on the possible use of flywheels was presented by the Goddard Space Flight Center to the entire Energy Storage Workshop. Although the ideas and rationale presented sounded reasonable, workshop members lacked the proper background to be able to judge this presentation. The Goddard group does feel that the paper studies already done on possible storage systems were encouraging enough to merit further development, leading to the ground testing of actual hardware. Current topical reports on the use of flywheels for energy storage are under review at Lewis. Much work at the conceptual design area has been carried out under ERDA/DOE programs. The Europeans are also considering flywheels as possible storage devices.

RESPONSE TO GUIDELINE QUESTIONS

Mission Model

The mission model indicates a continuing growth in power requirements to levels that are much higher than those prevailing at present. Fortunately, because of the modular nature of most energy storage devices, large variations in power level do not demand large variations in energy storage technology. A brute force approach to energy storage for high power levels is possible with present technology, but this approach is likely to be so heavy, complex, and costly that it effectively precludes many important applications. Since energy storage will be an important factor in any high power systems, advancements in energy storage technology must be pursued if the weight, complexity, and cost of such systems is to be kept within reasonable bounds. Several technology options with different risk-to-reward ratios are available for consideration.

Technology Goals

Probably the single most widely used basis for comparing energy storage devices is energy density (W·hr/lb or W·hr/kg). If such a basis is used, it is necessary to distinguish between the total energy density of a device and the usable energy density when constrained by mission requirements. It is also necessary to take into account special characteristics of a device, which affect the weight of other parts of the satellite. For this reason accurate comparisons of the energy density of various storage approaches can only be made for specific missions, and attempts to generalize may be very misleading. Recognizing these difficulties, some generalizations must still be attempted. All energy storage devices discussed in the workshop, except HEDB have, or are projected to have, total energy densities in the 20 to 30 W·hr/lb range. HEDB's are the only devices projected to significantly improve on this range to say 40 to 60 W·hr/lb. Since HEDB's are unlikely to be flight ready until after 1990, reasonable goals for energy storage by 1990 would appear

to be 30 W·hr/lb total energy density, with a requirement that a large fraction of this be usable. After 1990 goals of 40 to 60 W·hr/lb may be reasonable.

Adequacy of On-Going Programs and New Technology Required

Present Ni/Cd programs are probably adequate since highly developed cells are available in a variety of sizes from manufacturers and since nickel electrode and separator work applicable to Ni/Cd should continue under Ni/H_2 development. Evolutionary improvements in Ni/Cd's can be accommodated by manufacturers under competitive pressures with little or no government support. Revolutionary improvements would require government support, but it is unclear what revolutionary improvements are available to Ni/Cd's that would enable them to surpass Ni/H_2 on a total merit basis.

Present and planned Ni/H_2 programs are adequate from the standpoint of developing a flexible system of hardware configurations that should be suitable for general purpose use at all power levels anticipated into the 1990's. Present and planned Ni/H_2 programs are not designed to make significant improvements in separator and electrode technology or to develop battery design and charge control technology. Such work needs to be done to more fully realize the potential and accelerate the application of the Ni/H_2 system.

The planned NASA program in fuel cell/electrolysis appears to be inadequate for both LEO and GEO applications.

Present and planned near-term studies of flywheels and inductive energy storage are adequate for now. Increased attention to these systems in the future may be warranted as a result of these studies.

HEDB's offer the highest payoff and the highest risk for the long term (post 1990). Much basic and applied work will continue to be funded by DOE for terrestrial applications. Increased NASA funding now for space applications would be beneficial in a diffuse way, but should not be expected to dramatically accelerate the identification of a system suitable for space. When such an identification can be made and resources focused, an aggressive program should be pursued.

Delta Resources

No increase is required for Ni/Cd development unless cell case or cadmium electrode improvements are desired. Some separator and nickel electrode benefits will accrue to Ni/Cd indirectly, if our recommendations for work in these areas for Ni/H_2 are acted upon.

The greatest need for increased resources within NASA is for Ni/H_2 because of the very low level of current NASA activity here and the imminent flight readiness of the technology.

Some increase in resources is required for fuel cell/electrolysis to assess this technology for GEO applications.

Current resources are adequate for planned studies of flywheels (NASA) and inductive energy storage (Air Force).

The greatest uncertainty in resource allocation is related to HEDB's. Certainly work must be sustained at least at current levels and possibly increased. Once an HEDB clearly suitable for space applications can be identified, a sharp increase in resources should be justified.

Present Roles

Present roles associate Ni/Cd, fuel-cell/electrolysis, flywheel and HEDB with NASA; and Ni/H_2 and inductive and HEDB with the Air Force.

Future Roles

Present roles should change in only two areas - soon in Ni/H_2 and later in HEDB.

In Ni/H_2 the Air Force should pursue its present course in completing its system of hardware configurations. NASA should formulate a plan for increased Ni/H_2 involvement that builds on and complements Air Force activity.

The HEDB area is currently broad enough to justify and easily encompass nonduplicative efforts by both agencies. As progress occurs, technological targets are likely to converge to one or two preferred approaches. As this happens, increasing coordination will be required to define agency roles.

FLYWHEEL

Set Technology Objectives Needed - Assessment of Advanced Power Systems

. To develop concepts, perform feasibility analyses, and design and develop a power system utilizing inertial energy storage.

. To demonstrate that high overall system efficiency and reliability can be obtained for power systems with inertial energy storage.

Under previous study contracts the improvement in performance anticipated from a rotary energy storage system by incorporating magnetic bearings, electronic commutation, ironless armature construction, and vacuum operation into the design was evaluated. The study also evaluated the use of composite or super-flywheel construction practice compared with conventional high-strength steel. Results did not uncover any critical technical obstacles. A "best design" that identified the rim design, suspension system, and motor-generator design that offer the highest probability of meeting the goals of maximizing energy density, power density, and through-put efficiency greater than 90 percent was disclosed.

The effort proposed under this plan will extend the previously completed analysis to include the total power system. A feasibility study will examine various concepts for a multikilowatt power system using

mechanical energy storage. Comparisons with electrochemical systems will be made. Examples of items to be considered include power range, ac vs. dc operation, solar array design compatibility, system operating voltages and frequencies, distribution including power transfer across rotary joints, modularization of power units and power system, availability of off-the-shelf components, payload compatibility, and overall technical requirements and risk for the system. In addition, the feasibility study will define and scope the task required for a system definition phase. This initial effort will consummate with a study report.

The system definition phase will be performed under contract. The contractor will develop a detailed configuration for the advanced power system utilizing inertial energy storage. This effort will consist of system definition, breadboarding hardware, and in some cases building prototype hardware. Specific emphasis will be placed on the inertial energy storage unit and conversion and control electronics.

During previous studies, a limited test program identified problems in using conventional shaft driven test equipment to measure the performance of a floating rim design storage unit. Further work in this area is required to fully characterize the inertia storage device. The most effective approach is to build a scale model of an inertial storage unit and operate it as an integral part of a power system test. It is envisioned that the model would be capable of 2 to 3 kW hr of energy storage and contain all major power electronics, inverters, control loops, distribution equipment, and solar array simulator. Overall power system performance parameters would be characterized and the feasibility of modularized power system that could be cascaded into a much larger system (up to 25 kW) would be demonstrated.

WORKSHOP PARTICIPANTS

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Irwin M. Schulman	Jet Propulsion Laboratory
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FUEL CELL SET TECHNOLOGY OBJECTIVES - ONGOING[a,b]

- NO ACTIVITY IN EITHER FUEL CELLS OR BATTERIES SPECIFICALLY ORIENTED TOWARD GEO OPERATIONS: ONLY FOR LEO OPERATIONS
- H_2/O_2 FUEL CELL AND ELECTROLYZERS (REGENERATIVE FUEL CELL SYSTEMS) FOR LEO OPERATIONS
  - BREADBOARD FEASIBILITY DEMONSTRATION - 1982
  - ENGINEERING MODEL AND "TECHNOLOGY READINESS" DEMONSTRATION - 1985

FUEL CELL SET TECHNOLOGY OBJECTIVES - NEEDED[a,b]

I. ANALYTICAL STUDY FOR GEO OPERATIONS - DUTY CYCLE, CHARGE/DISCHARGE REQUIREMENTS, ETC.
   A. HYDROGEN/OXYGEN FUEL CELLS
   B. HYDROGEN HALOGEN FUEL CELLS

II. CELL TECHNOLOGY
   A. CELL SIZING
   B. CELL DEVELOPMENT
      1. LONG-TERM STORAGE (INACTIVE) EFFECTS
      2. ACTIVATION REQUIREMENTS
      3. CYCLIC DUTY

III. STACK TECHNOLOGY
   A. THERMAL MANAGEMENT
   B. MASS MANAGEMENT
   C. SCALE-UP

IV. BREADBOARD EVALUATION

V. ENGINEERING MODEL FIELD TESTING

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[a]All resource and schedule information are committee recommendations and do not reflect any commitment by NASA or by the Air Force.
[b]Submitted by Johnson Space Center personnel.

BATTERY SET TECHNOLOGY OBJECTIVES - NEEDED[a]

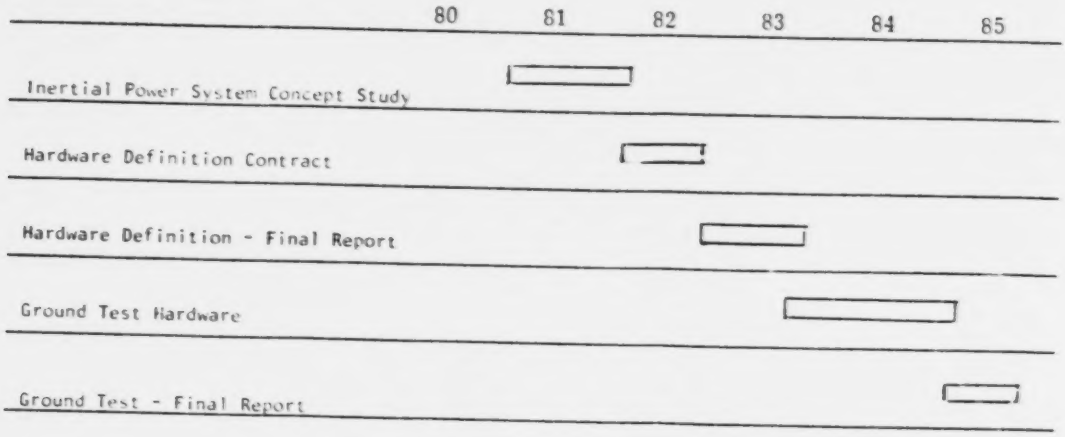
I. CELL EFFORT
- A. 200-250 AH $Ni-H_2$ CELL DEVELOPMENT
  1. SCALE-UP OF PRESENT AIR FORCE 50 AH TECHNOLOGY
  2. INCREMENTAL DEVELOPMENT FOR SCALE-UP PROBLEMS
- B. CONTINUED DEVELOPMENT OF Li-Al/FeS
  1. POTENTIAL FOR 10-YR LIFE, 40 W hr/lb, $100/kW hr
  2. APPLICATION SIMILARITIES TO TERRESTRIAL VEHICLE PROPULSION & LOAD LEVELING
  3. DEVELOPMENT EFFORT REQUIRED FOR APPLICATION TO GEO OPERATIONAL DIFFERENCES

II. BATTERY EFFORTS
- A. $Ni-H_2$ BATTERY
  1. ENGINEERING PROTOTYPE DEVELOPMENT
  2. PERFORMANCE EVALUATION
     a. V-A CHARACTERISTIC
     b. THERMAL CHARACTERISTICS
     c. LIFE POTENTIAL
     d. SAFETY AND OFF-LIMITS
- B. Li-Al/FeS
  1. AS CERTAIN APPLICABILITY OF PRESENT HARDWARE
  2. DEVELOP MODIFIED CELL/BATTERY PROTOTYPES
  3. PERFORMANCE EVALUATION (AS FOR $Ni-H_2$)

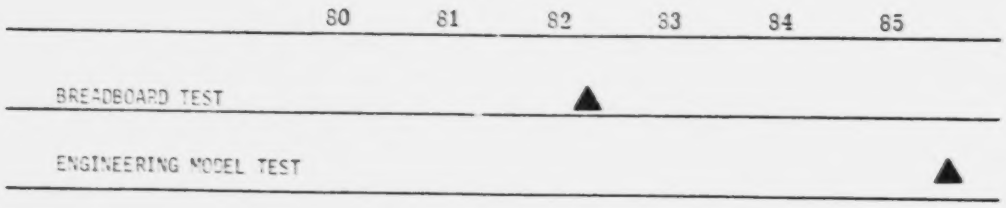
III. SYSTEM EVALUATION
- A. HIGH VOLTAGE PERFORMANCE CHARACTERISTICS
- B. CHARGE/DISCHARGE CONTROL
- C. THERMAL CONTROL
- D. MODULAR PACKAGING CONCEPT
- E. REPLACEMENT PHILOSOPHY

[a]All resource and schedule information are committee recommendations and do not reflect any committment by NASA or by the Air Force.

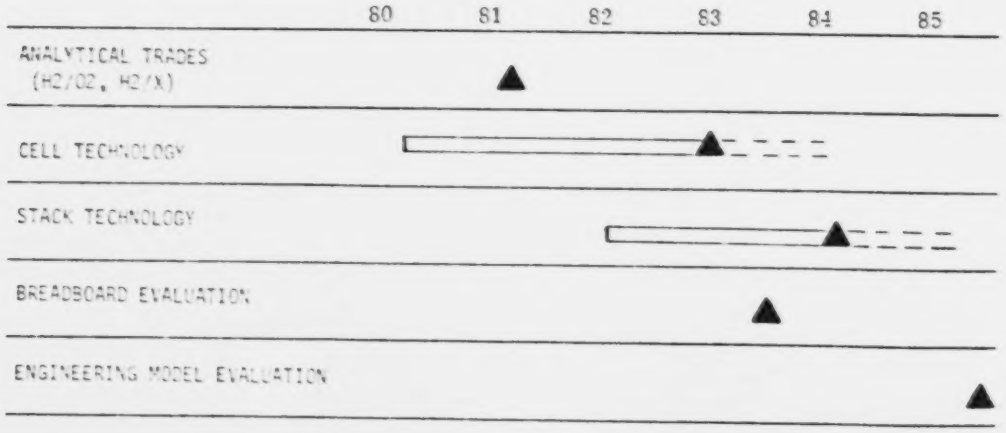
G-NEW TECHNOLOGY TARGETS



ONGOING TECHNOLOGY TARGETS
(JSC)



NEW TECHNOLOGY TARGETS
(JSC)



POWER MANAGEMENT WORKSHOP[1]

The objective of the Power Management Workshop was to review the NASA/Air Force High Orbit Spacecraft Energy Technology Program concept, define the elements of present programs which will meet the technology goals presented, identify areas of new technology not presently under development, and estimate any "delta" resources required to meet the program requirements.

MISSION MODEL

The Power Management panel reviewed the mission model, discussed the basic assumptions, and made comparisons to space power systems of past and future (25-kW power module) spacecraft. In general the panel felt the mission model was a good one, though ambitions in some areas.

(1) The payload capability of the Shuttle-IUS to insert the mission model into geosynchronous orbit is 2269 kg. This will place a severe weight limit on some of the subsystems. Of major concern is the solar array and energy storage subsystems.

(2) The proposed energy storage capacity was 2-1/2 kW hr during eclipse. Powering down during eclipse places an undesirable limitation on the overall capability of the system. A vigorous technology effort is recommended to significantly lower the specific mass (g/J) of the energy storage subsystem.

(3) The mission model is expected to service a number of users whose requirements may differ from each other and may change during the life of the mission model. Concerns were raised about the power system obsolescence. It was recommended that the power system be flexible to easily accommodate different users. The user must be expected to do some of the fine tuning peculiar to his system requirements.

TECHNOLOGY GOALS

The mission model proposed is a geosynchronous, free-flyer power station capable of providing 25 kW of regulated power during daylight and an energy capacity of 2.5 kW·hr during eclipse. A thermal control subsystem will be capable of rejecting 28 kilowatts of heat. Users will be able to reject 25 kW to the power station by means of a simple thermal interface and a 3-kW capability would be provided to reject power conversion and distribution losses. Additionally the power station must be compatible with a Shuttle-IUS interface.

The panel discussed the effect of these base requirements on the power

[1]All resource and schedule information are committee recommendations and do not reflect any committment by NASA or by the Air Force.

subsystem and attempted to identify the technology advances necessary to meet the goals. Results and recommendations are shown in table 1.

Historically, power systems have accounted for approximately one-third of the spacecraft weight. The power system was assumed to include solar arrays, power conditioning, including distribution and control, and energy storage. Using this ratio, the power system weight budget would be approximately 700 kg. By 1985 technology advances in components and circuit techniques should provide high power converters with a specific mass of about 1 kg/kW. It is estimated that the distribution and control, including the rotary power transfer device, switch gear, distribution buses, and power interfaces at the user point of load can be achieved within 2 kg/kW. As shown in figure 2 the technology goal for power conditioning and distribution is recommended at 3 kg/kW or 75 kg. If the 700 kg assumed for the power system is valid, approximately 625 kg would be available for solar arrays and energy storage. As mentioned previously this places severe weight limits on these subsystems.

During the discussion of the effect of the distribution voltage on the weight of power conditioning and distribution, references were made to previous studies which show that significant reductions in weight can be realized in the 300- to 400-volt range. Interactions between high voltage and the space environment are a concern, and it is recommended that performance verification experiments be carried out to eliminate uncertainties. The 400 volts should provide a reasonable derating for semiconductors. The final choice of the voltage should be based on weight, losses, and reliability to meet the life time requirement.

Should the power distribution be ac or dc? Pros and cons were discussed. Some of the benefits of an ac system would be simpler switch gear - which could be activated when the current goes through zero to minimize transient interactions - and a simpler power interface at the user location with a "split" transformer and the ability to step the voltage up or down to match the user. The workshop members felt more work needs to be done to define the ac benefits and problems and to demonstrate the ac system proof of concept. The members recommend that continued emphasis be placed on a dc distribution system. A concern was raised that an ac system might be electromagnetically visible and therefore detectable.

Autonomous fault protection. - The power station concept must be capable of providing regulated power to different users with different demands, and it must perform for at least 10 years. Care must be taken to insure that user faults or internal system faults do not lead to catostrophic failures. The members felt that autonomous fault protection is a must for such an unmanned satellite. This self-protection feature should be included at the outset of the system design with preliminary definition and breadboard demonstration preceding the design.

Radiation hardness. - In the discussion dealing with the requirement of 10-year lifetime, concerns were raised about radiation hardness. Marshall Space Flight Center (MSFC) had recently studied radiation effects on a power converter using conventional bipolar transistors and has determined that shielding will be required to meet a 5-year life. The shielding will increase the mass between 10 and 15 percent. The potential radiation effects on present-day semiconductors and components should be studied for the geosynchronous orbit.

Modeling and analysis. - The proposed geosynchronous 25-kW power

station will focus a number of new technologies into a new system. The performance of the subsystems and interactions between those subsystems are largely unknown. Modeling and analysis of the system performance would be an invaluable guide to help the system designer uncover potential performance problems before "cutting" hardware. One example of the problems that might come up is the interactions between the solar array and the power converters whose input impedance is negative. The PM panel recommends an early effort in system performance modeling and analysis.

Reliability. - One of the major drivers will be reliability. Concerns were raised that 10-year lifetimes will be difficult to achieve for a high voltage, high power station in the geosynchronous environment.

In conclusion on technology goals, the members recommend that a low Earth orbit test should be performed to verify the design approach.

DEFINE ELEMENTS OF PRESENT PROGRAMS WHICH WILL MEET TECHNOLOGY GOALS

As shown in table II, the Air Force Wright Aeronautical Laboratories (AFWAL) and NASA Lewis Research Center have technology programs to develop power converters with a goal of 1 kg/kW (packaged) at 25 kilowatts. Target dates for this technology is 1982.

Autonomous fault protection technology is being developed for aircraft power systems by AFWAL and for space power systems by NASA Marshall Space Flight Center. Both agencies are well along in their programs and feel this technology could easily be adapted to the proposed GEO power station.

Four major studies are in progress which will be helpful in focusing technology approaches. AFWAL has a study to develop a conceptual design of a high voltage high power system. NASA Goddard Space Flight Center has two efforts: (1) the development of ac/dc model for 2-to 15-kW power subsystem and (2) a study of inertial energy for space power systems. Outputs of these studies may enter in the resolution of ac versus dc distribution systems. An "on array" regulation study has been studied by NASA Lewis to identify the characteristics of a solar array switching approach to power management and estimate the benefits that could be achieved.

NASA Marshall is presently developing a high voltage dc (300 V) system. Power conversion is accomplished with a programable power processor (P^3) which is a 3-kW buck converter capable operating over a broad input range up to 300 volts. Components and subsystems are also in progress.

NASA Lewis has an on going program to provide the technology of high voltage, high power components, transmission lines, rotary power devices, and power converters. Prototype 25-kW transistorized switch gear should be ready by 1982. Additionally a technology effort is under way to develop an ac power converter.

IDENTIFY NEW TECHNOLOGY REQUIRED FOR THE PROGRAM

The workshop members have identified the new technology efforts (see table III) that would be required for the geosynchronous 25-kW power station program.

1. Satellite high-frequency studies should be carried out to define and quantify electromagnetic visibility and detectability.

2. A power system tradeoff study should be performed to determine distribution voltage, type of distribution (ac or dc), power conversion approach, point of load, and input interface requirements and to develop a preliminary power system design. An assessment should be made of an inertial energy storage subsystem to determine its advantages for the proposed power station concept.

3. System performance modeling techniques should be developed to guide system designers.

4. Radiation hardened components should be developed for long life geosynchronous application.

5. Technology readness should be demonstrated through performance verification tests. LEO experiment tests should be performed to eliminate uncertainties.

6. A technology effort should be initiated to perform an ac system proof of concept. Major ac components should be developed and tested at the subsystem level.

Estimated resources are shown in table IV.

WORKSHOP PARTICIPANTS

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TABLE I. - TECHNOLOGY GOALS

(1) HIGHER SPECIFIC POWER IS A MAJOR ISSUE

HISTORICALLY POWER SYSTEM WEIGHT IS ≈1/3 SPACECRAFT WEIGHT

SOLAR ARRAYS AND ENERGY STORAGE	600 kg
POWER CONDITIONING AND DISTRIBUTION[a]	100 kg
	700 kg

BUT A MAJOR PROBLEM EXISTS FOR SOLAR ARRAYS AND ENERGY STORAGE FOR AN IUS LAUNCH (2269 kg)

(2) DISTRIBUTION VOLTAGES SHOULD BE IN THE 300-400 V RANGE

(3) AC VERSUS DC

AF IS CONCERNED ABOUT ELECTROMAGNETIC VISIBILITY AND DETECTABILITY OF AN AC SYSTEM.

CONTINUE EMPHASIS ON DC SYSTEM WHILE DEFINING AC SYSTEM BENEFITS AND PROBLEMS.

(4) AUTONOMOUS FAULT PROTECTION IS A MAJOR CONCERN

(5) RADIATION HARDNESS MAY BE A LIMITING FACTOR ON LIFETIME

(6) SYSTEM PERFORMANCE MODELING AND ANALYSIS

(7) LEO TEST SHOULD BE PERFORMED TO VERIFY DESIGN APPROACH

(8) RELIABILITY TO MEET 10-YEAR LIFE IS A CONCERN, MODULARITY IMPACT MUST BE ASSESSED

[a]COULD BE DONE AT 75 kg.

TABLE II. - ELEMENTS OF PRESENT PROGRAMS WHICH WILL MEET TECHNOLOGY GOALS

AFWAL	- POWER PROCESSING AT 1 kg/kW (PACKAGED) IN DEVELOPMENT
	- AIRCRAFT AUTONOMOUS FAULT PROTECTION PROGRAM
	- HVHPS STUDY PROBABLY WILL MEET GOAL OF A SUITABLE CONCEPTUAL DESIGN
NASA Goddard	- AC/DC MODEL FOR POWER SUBSYSTEM (2 - 15 kW) TO START '80
	- INERTIAL ENERGY STORAGE IN PROGRESS HELPS IN RESOLUTION OF AC VERSUS DC
NASA Marshall	- AUTOMATED POWER MANAGEMENT TECHNIQUES IN DEVELOPMENT
	- PRESENTLY DEVELOPING A HIGH-VOLTAGE DC (300 V) SYSTEM
	- COMPONENT AND SUBSYSTEM DEVELOPMENT
NASA Lewis	- ARRAY REGULATION STUDY HAS BEEN STARTED
	- DEVELOPING COMPONENTS FOR A DC SYSTEM
	- PURSUING THE DEVELOPMENT OF AN AC POWER CONVERTER
	- PURSUING TRANSMISSION LINE TECHNOLOGY
	- DC SWITCH GEAR SHOULD BE READY IN '82

TABLE III. - NEW TECHNOLOGY REQUIRED FOR THE PROGRAM

AFWAL	- SATELLITE HF "VISIBILITY" STUDIES TO DEFINE HF DETECTION PROBLEM
	- SYSTEM MODELING AND TESTS SHOULD BE PERFORMED
NASA Goddard	- EXTENSION OF ANALYTICAL MODELING TO 25 kW LEVEL IS NEEDED
	- ASSESS IMPACT OF INERTIAL ENERGY STORAGE POWER SYSTEM FOR THIS APPLICATION
NASA Marshall	- DEVELOP RADIATION HARDENED COMPONENTS
	- PERFORMANCE VERIFICATION TO GEO ENVIRONMENT
NASA Lewis	- PERFORM POWER SYSTEM TRADE-OFF STUDY
	- PERFORM AC SYSTEM PROOF OF CONCEPT
	- DEVELOP MAJOR AC COMPONENTS AND PERFORM VERIFY TECHNOLOGY READINESS

TABLE IV. - NEW TECHNOLOGY RESOURCES

	82 $/MY	83 $/MY	84 $/MY	85 $/MY
NASA Goddard	50	150	150	50
NASA Lewis	150	500	300	50
NASA Marshall	150	100	100	50
AFWAL	100	200	200	--